Quarkonium production in 2.76 TeV PbPb collisions in CMS

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School of Collective Dynamics in High Energy Collisions

May 16th, 2012

QUARKONIA

1. Quarkonia are very "unusual" hadrons

heavy quark ($\bar{Q}Q$) bound states stable under strong decay

- heavy: $\mathbf{m_c} \simeq 1.2 - 1.4$ GeV, $\mathbf{m_b} \simeq 4.6 - 4.9$ GeV
- stable: $\mathbf{M_{\bar{c}c}}$ - 2$\mathbf{M_B}$ **<< 0** and $\mathbf{M_{\bar{b}b}}$ - 2$\mathbf{M_D}$ **<< 0**

What is "usual"?

- light quark ($q\bar{q}$) constituents
- loosely bound, $\mathbf{M}_\rho - 2\mathbf{M}_\pi \gg 0$, $\mathbf{M}_\Phi - 2\mathbf{M}_K \simeq 0$

- hadronic size ~ $1/\lambda_{QCD} \simeq 1$ fm, independent of mass

(At T = 0 Cornell potential gives full spectroscopy)

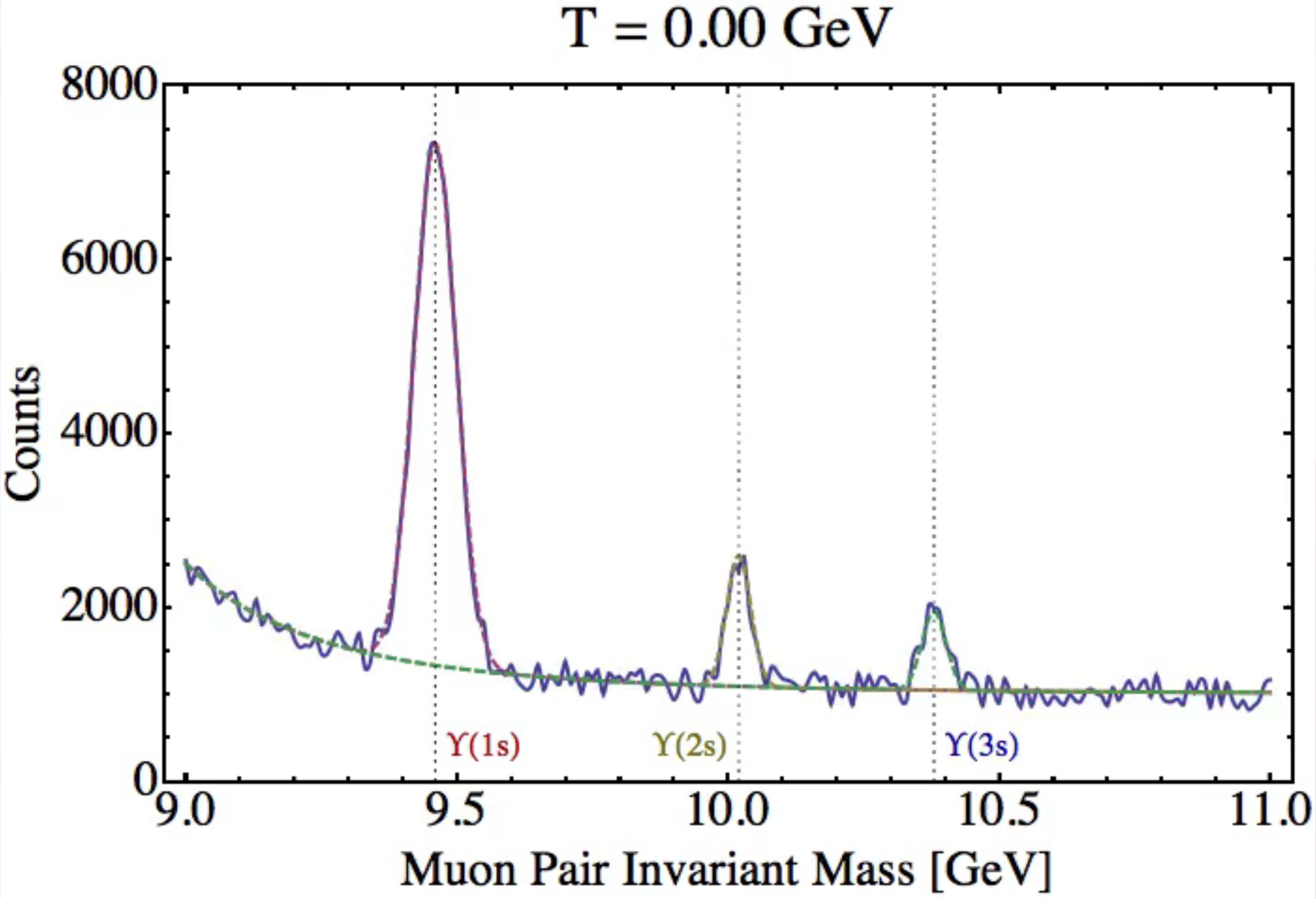
state	J/ψ	ψ'	Υ	Υ'	Υ''
mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
radius [fm]	0.25	0.45	0.14	0.28	0.39

Relativistic Heavy Ion Physics
By F Becattini, P Braun-Munzinger, Rainer Fries, C Gale, J. Schaffner-Bielich

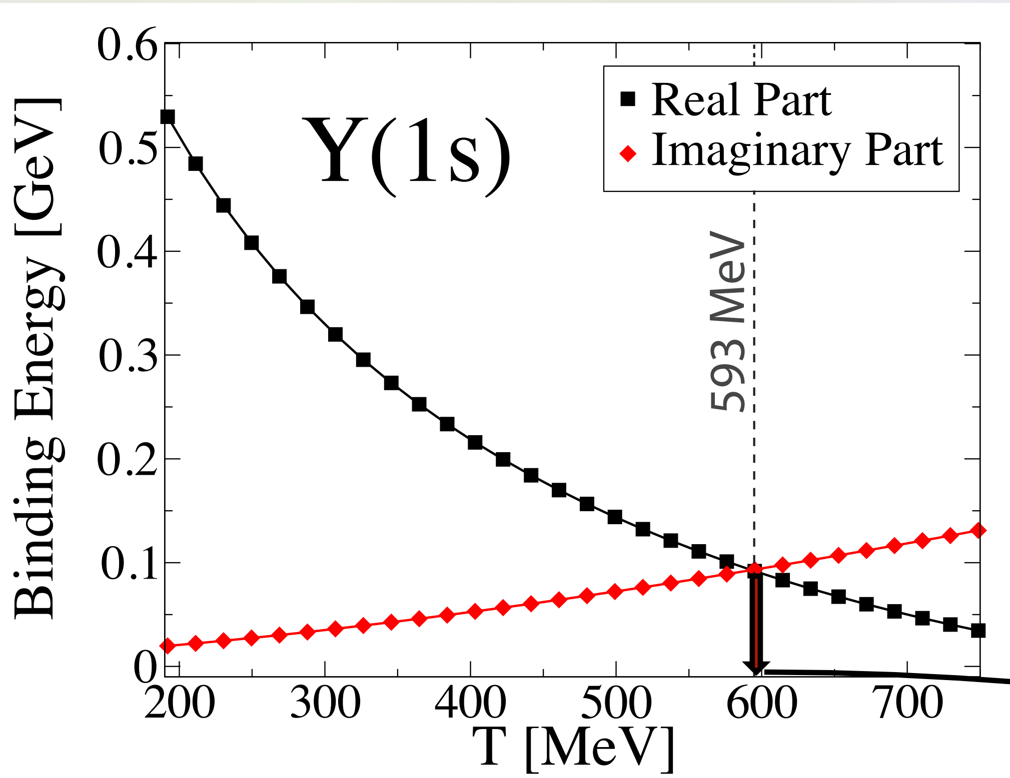
DEBYE SCREENING

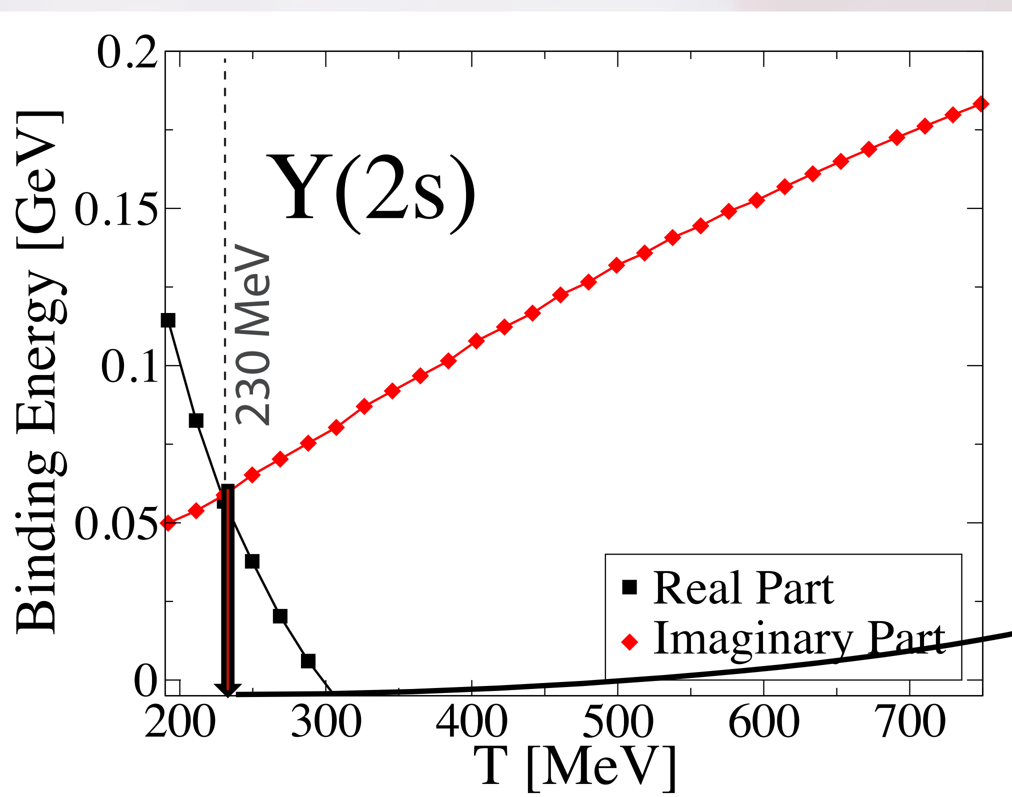
- In a high temperature quark gluon plasma we expect weaker color binding (Debye screening + asymptotic freedom)

- Also, high energy plasma particles which collide with bound states cause them to have shorter lifetimes → larger spectral widths



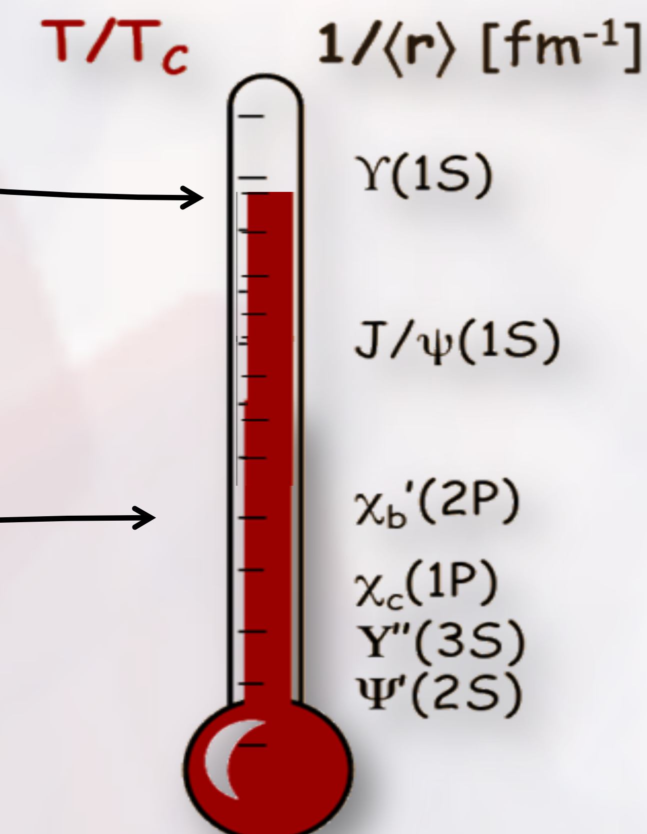
Sequential Melting





- Sequential Melting due to the Debye screening.
- Helps quantify medium properties (temperature)

A.Mocsy arXiv:0811.0337



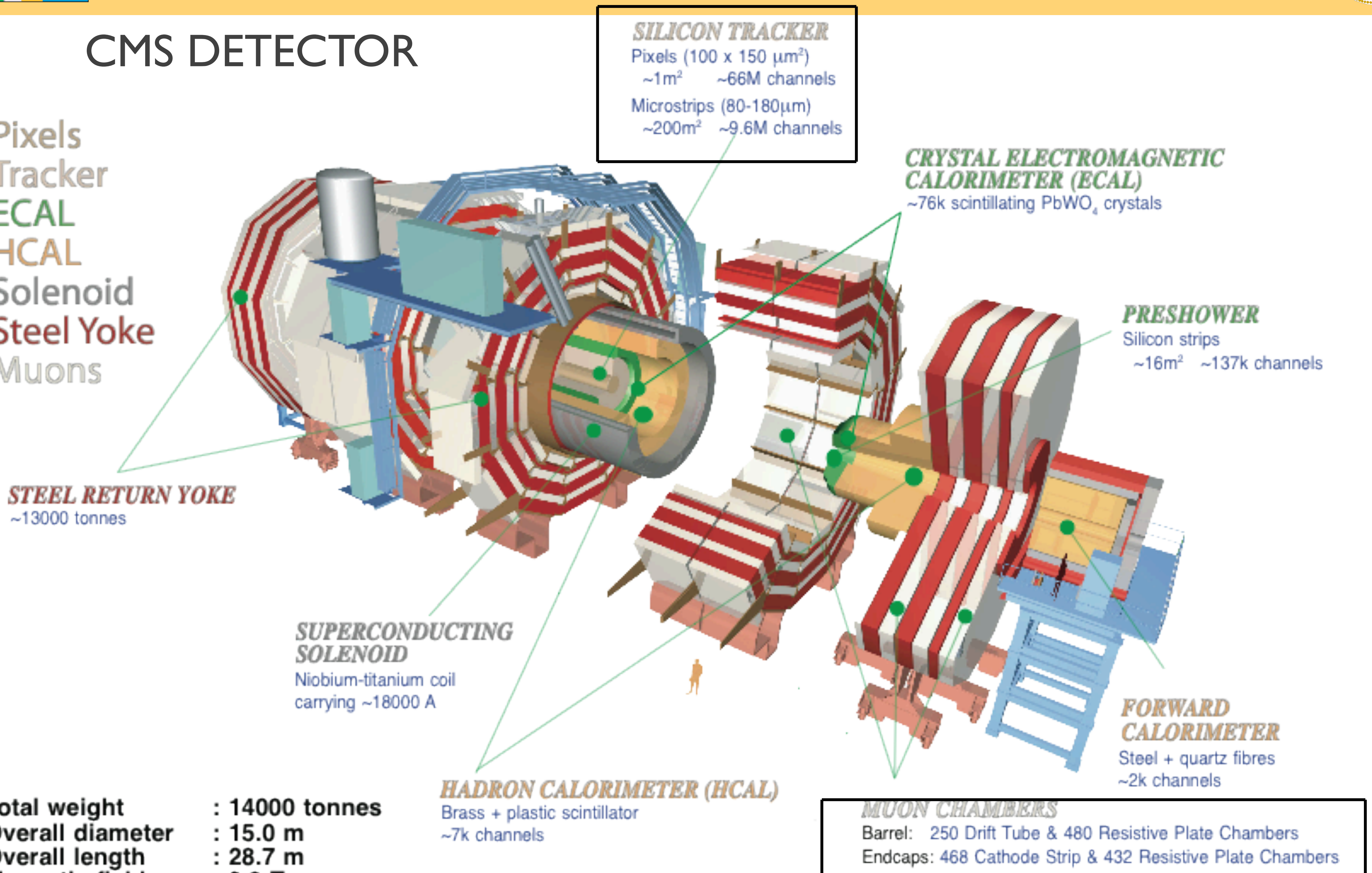
When does it dissociate?

Strickland et al (2011) (arXiv:1101.4651)

The Compact Muon Solenoid

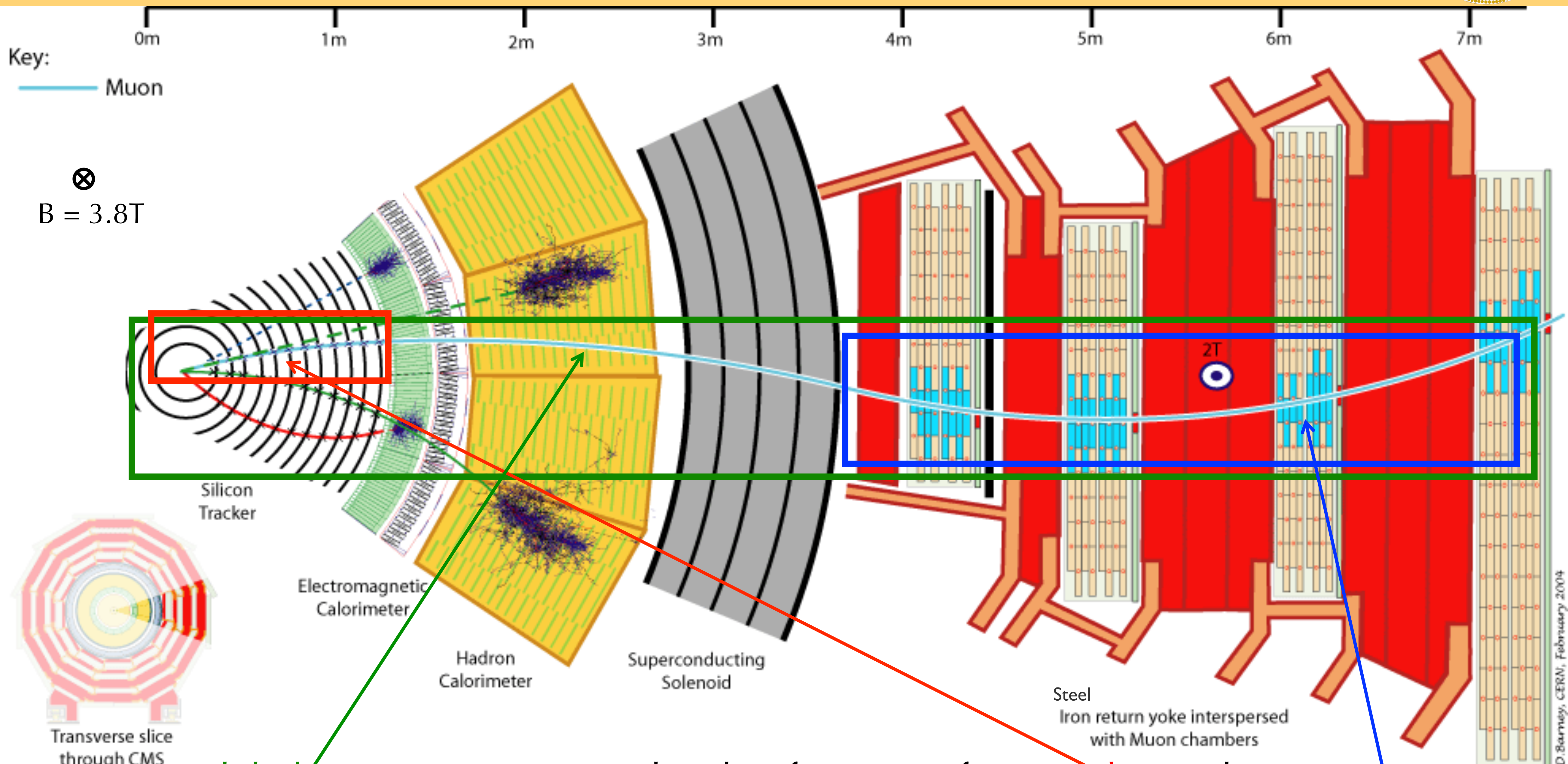
CMS DETECTOR

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



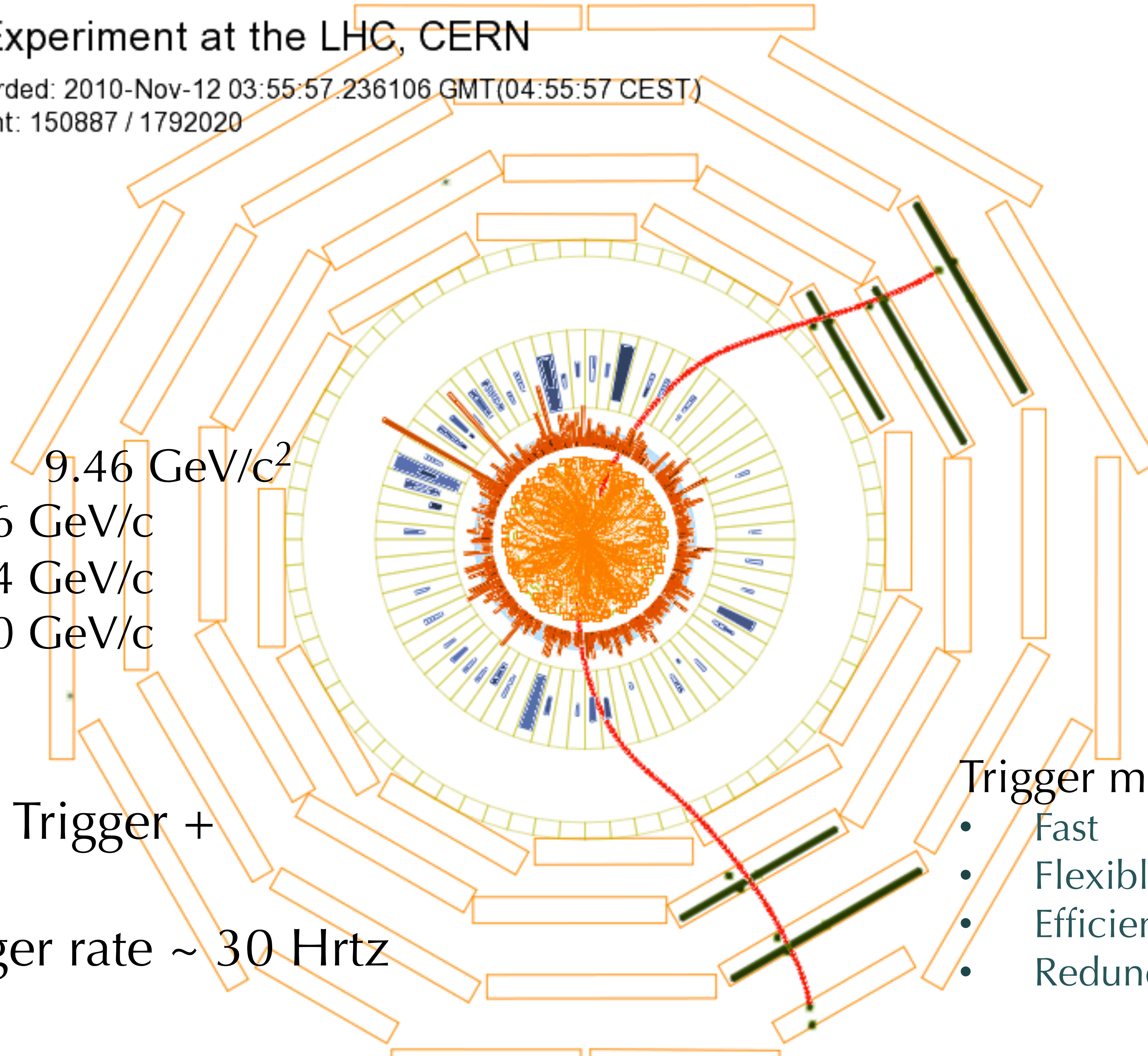
Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Muon reconstruction in CMS



- Global muons reconstructed with information from tracker and muon stations
- Muons need to overcome the magnetic field and energy loss in the absorber → need a minimum momentum of p~3–5 GeV/c to reach the muon stations
- Further muon ID based on track quality (χ^2, # hits,…)

Υ candidate in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



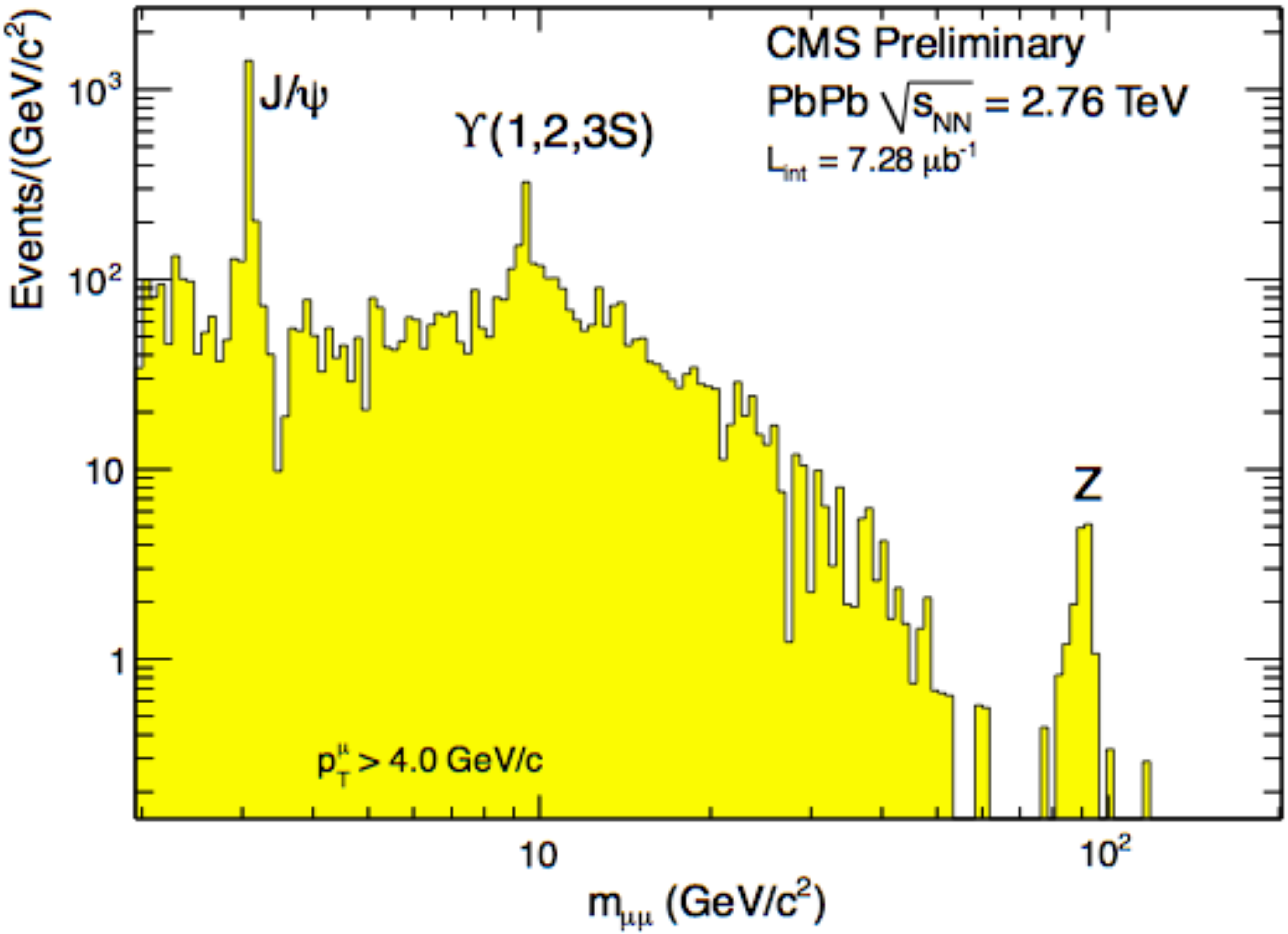
$\mu^+\mu^-$ pair:mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
μ^+:p_T = 4.74 GeV/c
μ^-:p_T = 4.70 GeV/c

Hardware L1 Trigger +
HLT
Dimuon trigger rate ~ 30 Hrtz

Trigger must be:

- Fast
- Flexible
- Efficient (95 %)
- Redundant

Muon pairs in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV



J/ψ and $\Upsilon(1S)$ suppression in PbPb at 2.76 TeV

- Detailed paper based on 2010 data
- First measurements of Nuclear modification factor (R_{AA}) for:
  - non-prompt J/ψ (from B decays)
  - prompt J/ψ
  - $\Upsilon(1S)$
- R_{AA} as a function of:
  - centrality: non-prompt J/ψ, prompt J/ψ, $\Upsilon(1S)$
  - p_T: prompt J/ψ, $\Upsilon(1S)$
  - rapidity: prompt J/ψ, $\Upsilon(1S)$

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}(\mathrm{cent})}$$

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2011-170
2012/01/25

CMS-HIN-10-006

arXiv:1201.5069v1 [nucl-ex] 24 Jan 2012

Suppression of non-prompt J/ψ, prompt J/ψ, and $\Upsilon(1S)$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The CMS Collaboration*

Abstract

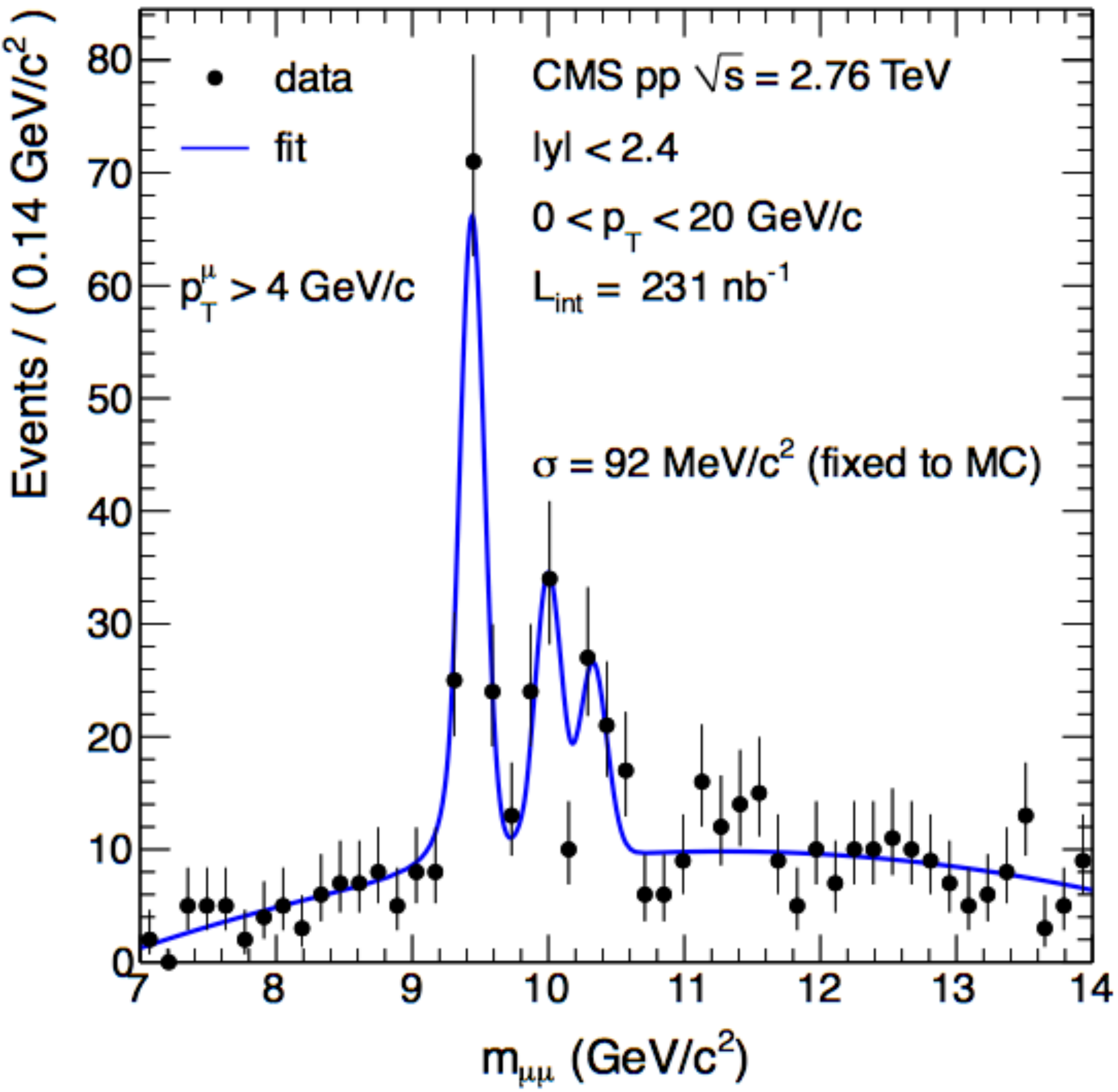
Yields of prompt and non-prompt J/ψ, as well as $\Upsilon(1S)$ mesons, are measured by the CMS experiment via their $\mu^+\mu^-$ decays in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV for quarkonium rapidity $|y| < 2.4$. Differential cross sections and nuclear modification factors are reported as functions of y and transverse momentum p_T, as well as collision centrality. For prompt J/ψ with relatively high p_T ($6.5 < p_T < 30$ GeV/c), a strong, centrality-dependent suppression is observed in PbPb collisions, compared to the yield in pp collisions scaled by the number of inelastic nucleon-nucleon collisions. In the same kinematic range, a suppression of non-prompt J/ψ, which is sensitive to the in-medium b-quark energy loss, is measured for the first time. Also the low-p_T $\Upsilon(1S)$ mesons are suppressed in PbPb collisions.

Submitted to the Journal of High Energy Physics

*See Appendix B for the list of collaboration members

Accepted to JHEP (arXiv:1201.5069)

$\Upsilon(nS)$ in pp at $\sqrt{s} = 2.76$ TeV

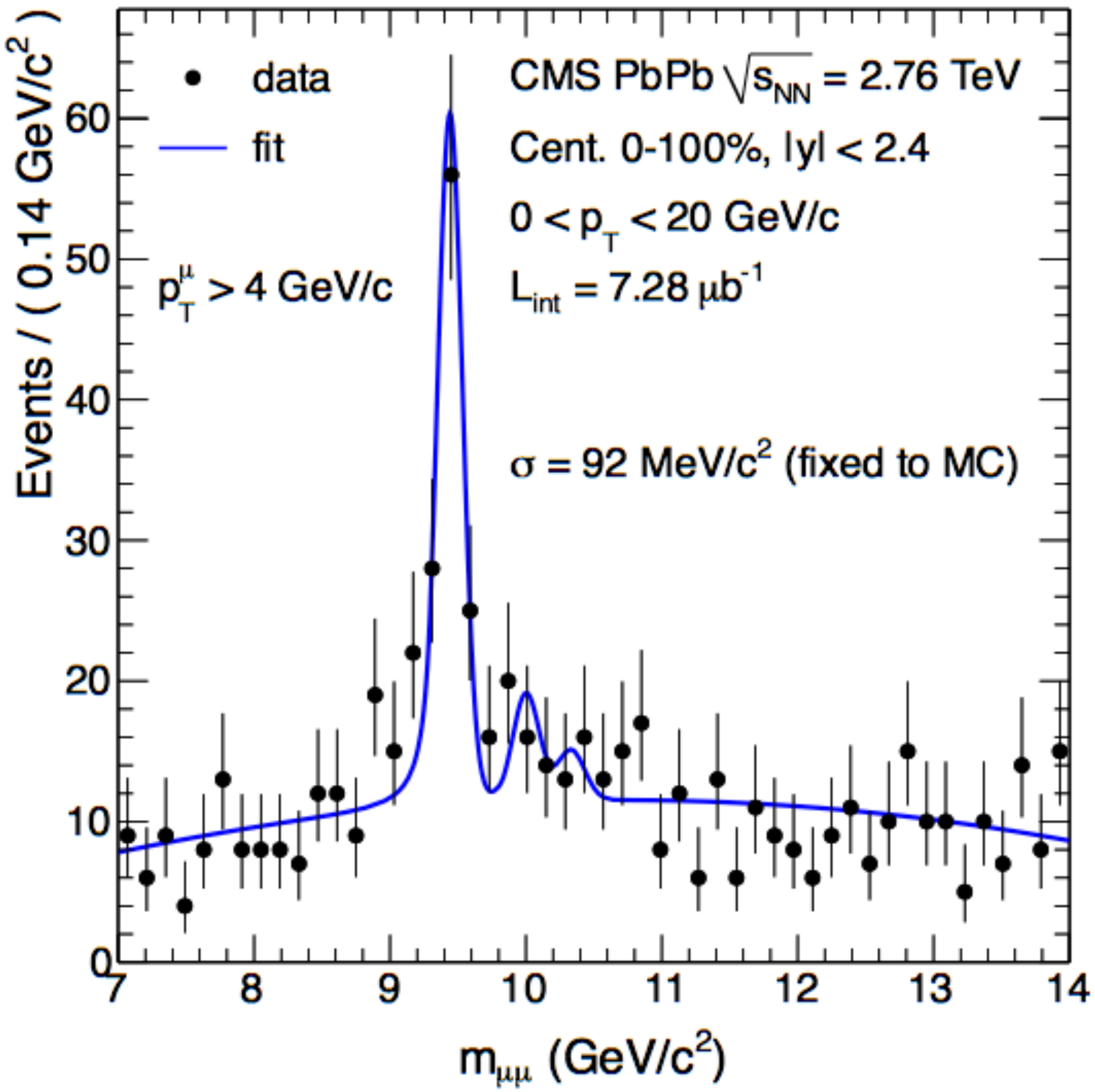


$$N_{\Upsilon(1S)} = 101 \pm 12$$

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

- Signal shape: sum of three Crystal Ball functions
- Background: 2nd order polynomial
- Free parameters:
  - Υ(1S) mass
  - Υ(1S) yield
  - Υ(2S+3S)/Υ(1S) yield ratio
  - Υ(2S)/Υ(1S) yield ratio
- Mass ratios of higher states fixed to PDG
- Υ(1S) resolution fixed from MC: 92 MeV/c^2
  - Consistent with fits when leaving resolution free (both in pp and PbPb)
- Resolution of higher states fixed to scale with mass ratio $\sigma_{2S} = m_{2S}/m_{1S}\ \sigma_{1S}$
  - Crystal Ball radiative tail fixed to MC

Υ(nS) in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



$$N_{\Upsilon(1S)} = 86 \pm 12$$

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

- Signal shape: sum of three Crystal Ball functions
- Background: 2^{nd} order polynomial
- Free parameters:
  - Υ(1S) mass
  - Υ(1S) yield
  - Υ(2S+3S)/Υ(1S) yield ratio
  - Υ(2S)/Υ(1S) yield ratio
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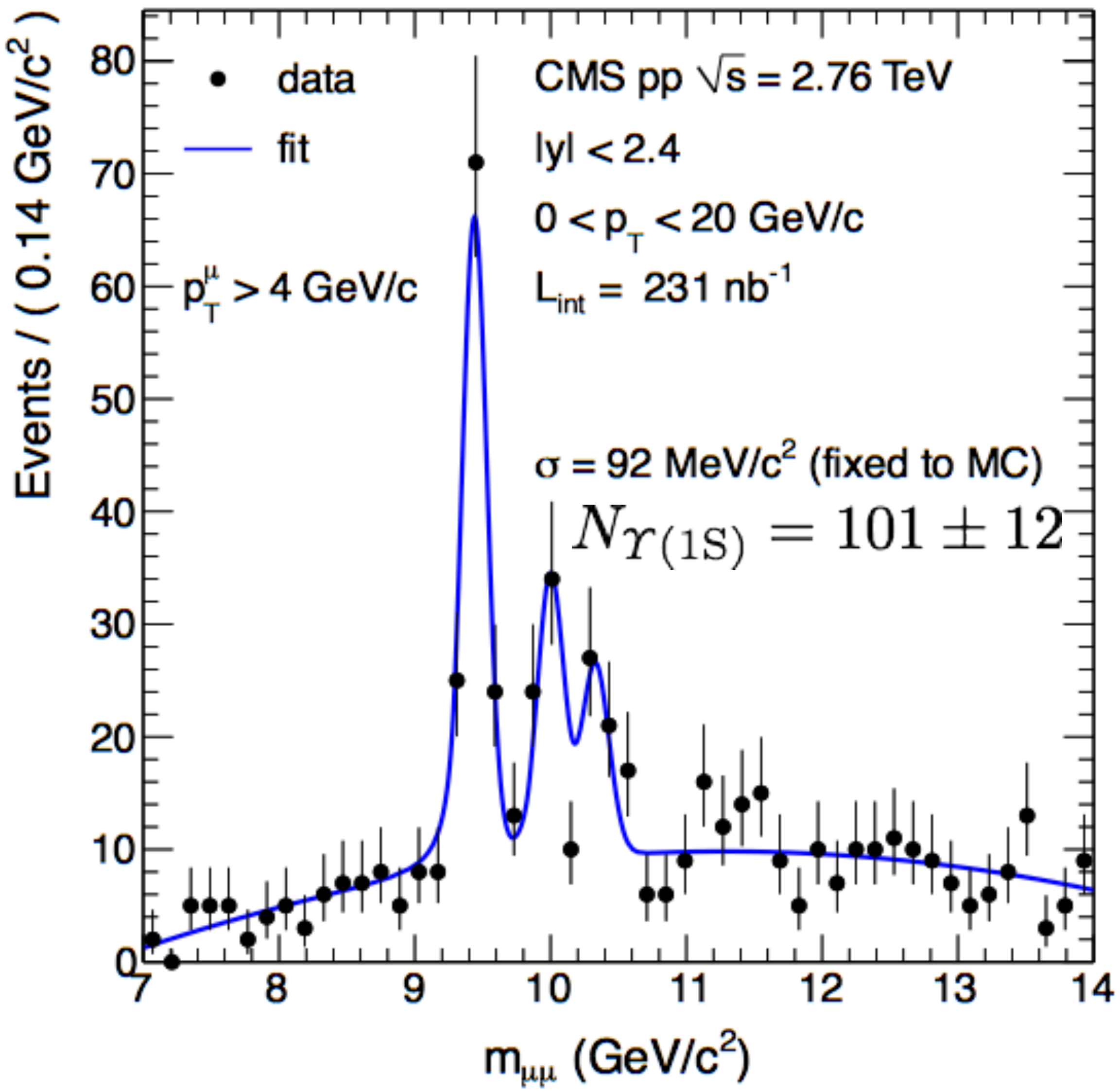
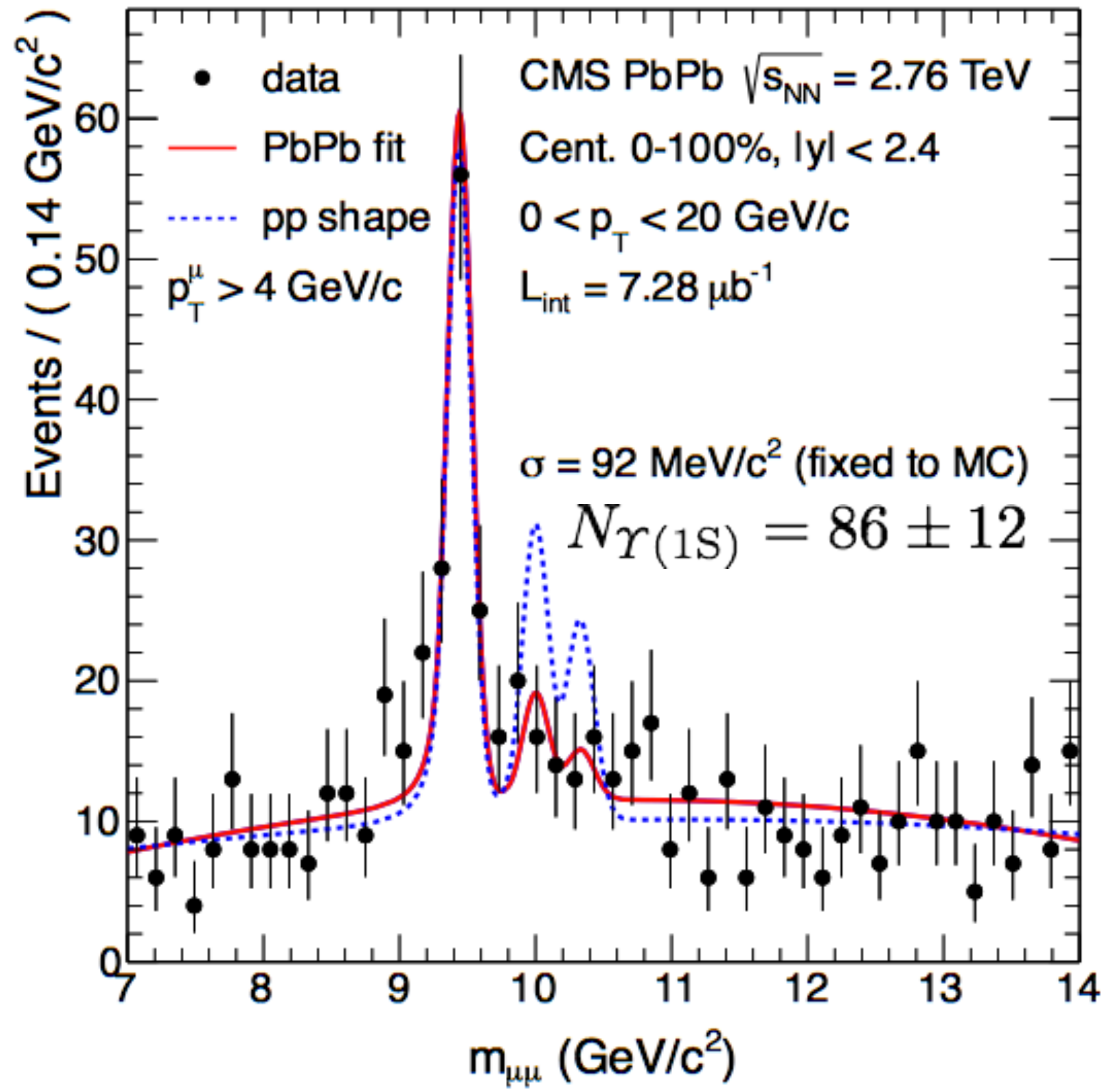
  - Crystal Ball radiative tail fixed to MC

Υ(2S+3S) Suppression



$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$



$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

- Measure Υ(2S+3S) production relative to Υ(1S) production

PRL 107 (2011) 052302

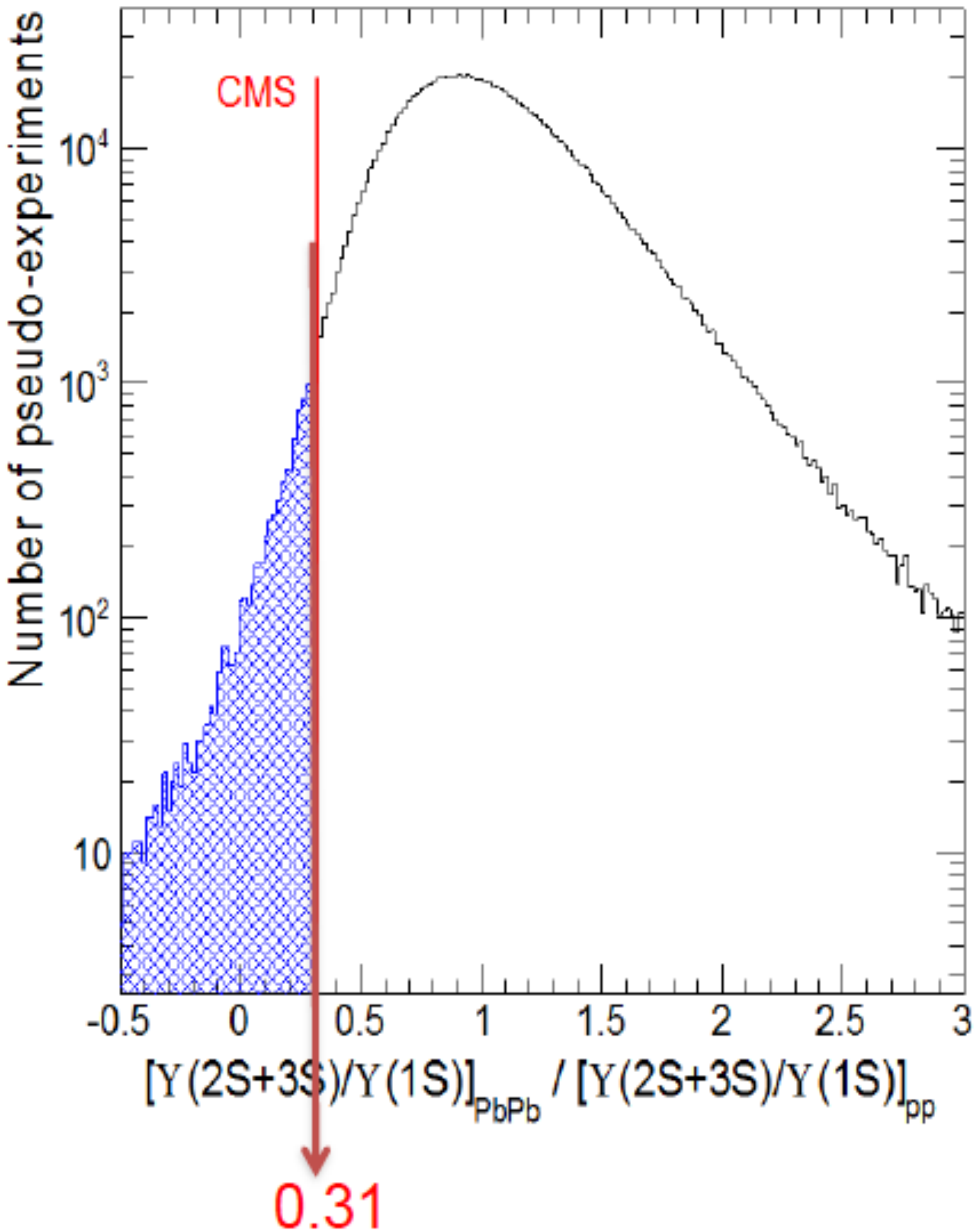
- Simultaneous fit to pp and PbPb data at 2.76 TeV

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

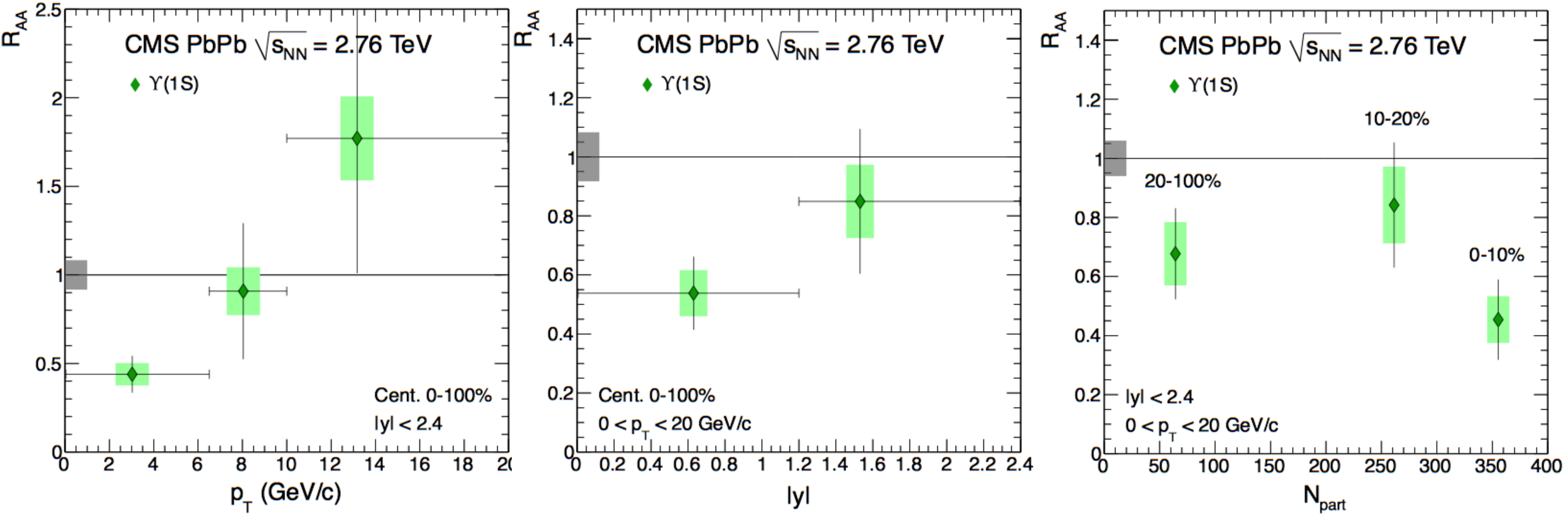
p-Value

Could background fluctuation produce a result as extreme as observed in data?

- Generate pseudo-experiments following the *null-hypothesis* (i.e. no suppression)
- Fit pseudo-data samples with nominal fit
- Count fraction of occurrences for which the ratio (taken as test statistic) is same or lower than observed:
  - p-value: 0.9%
  - 2.4σ (1-sided Gaussian test)



ϒ(1S) RAA

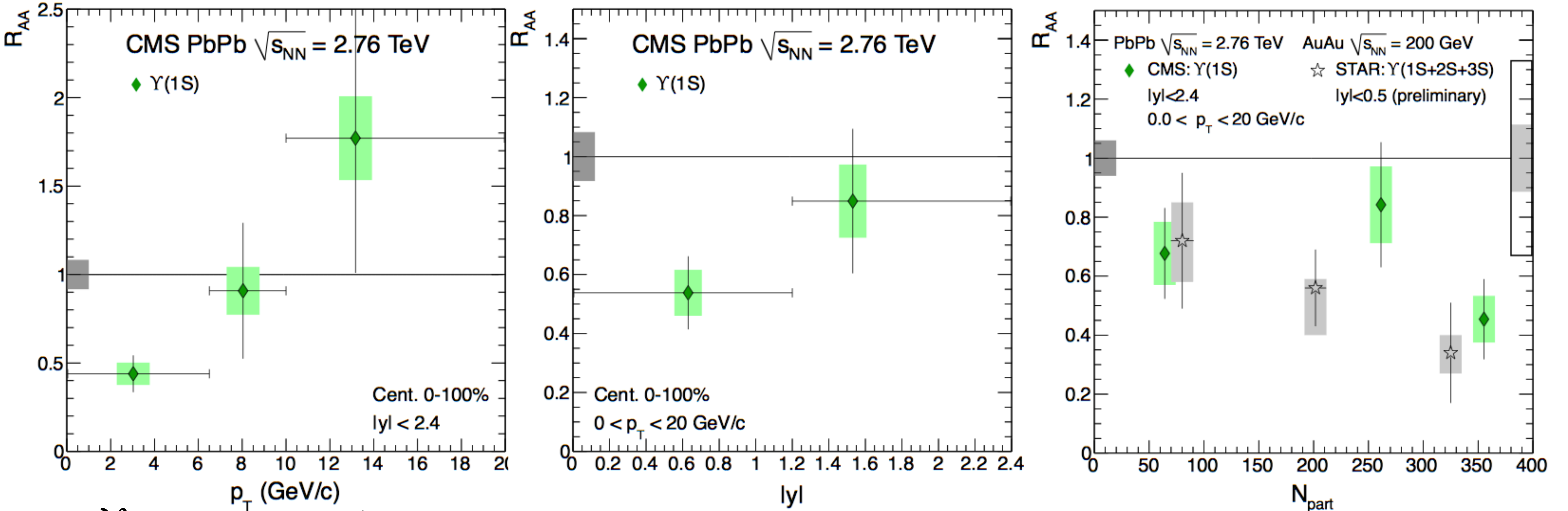


- ϒ(1S) suppressed at low p_T
- No obvious rapidity dependence
- CMS: ϒ(1S)
  - suppressed by factor ~2.2 in 0–10%
- Large feed down contribution from excited states (χ_b, ϒ(2S), ϒ(3S))
  - Observed ϒ(1S) suppression consistent with melting of excited states only

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(\Upsilon(1S))}{N_{pp}(\Upsilon(1S))} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb(cent)}}}$$

arXiv:1201.5069
(accepted to JHEP)

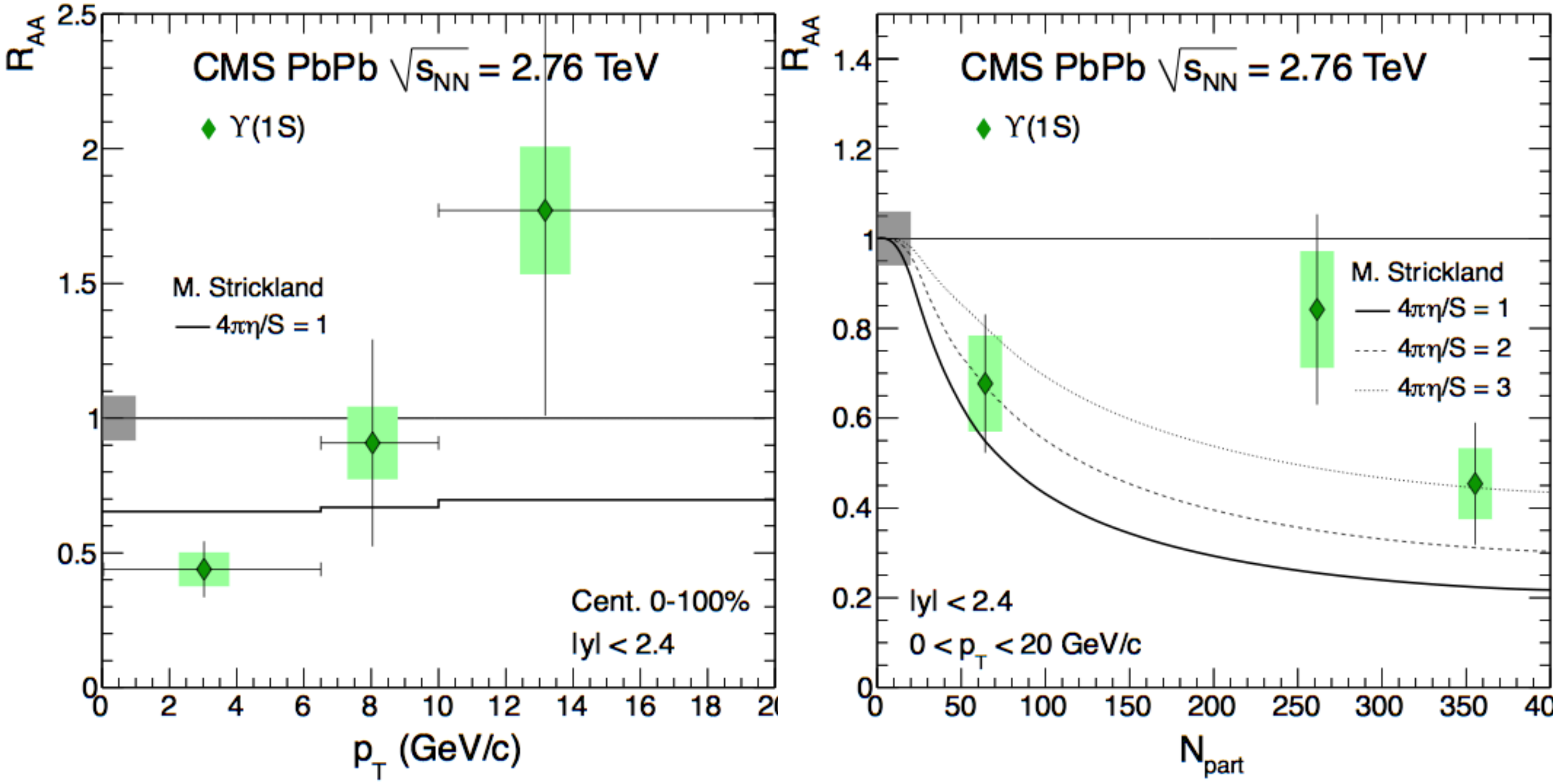
Υ(1S) R_{AA}

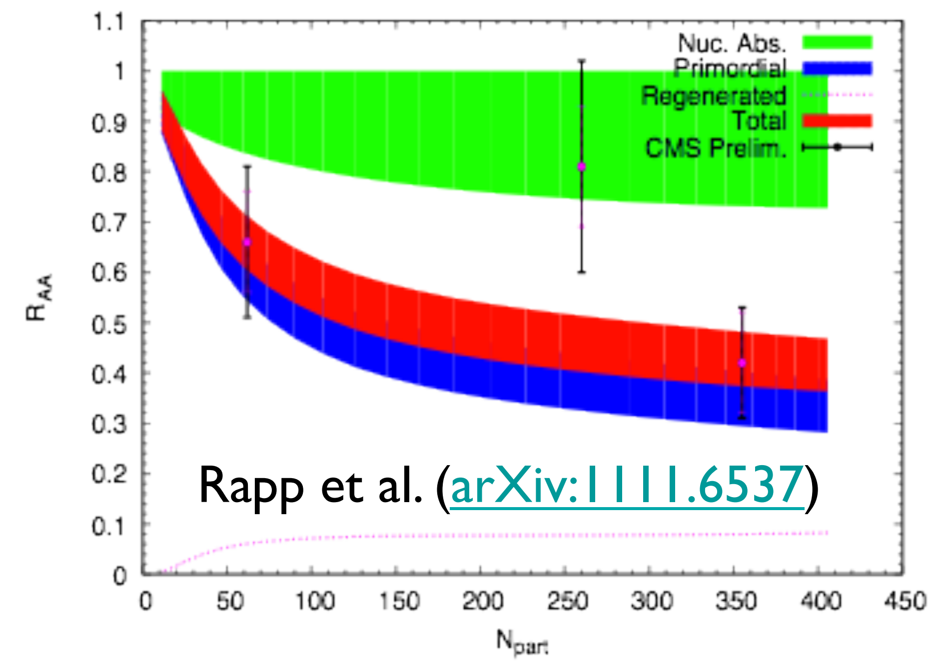


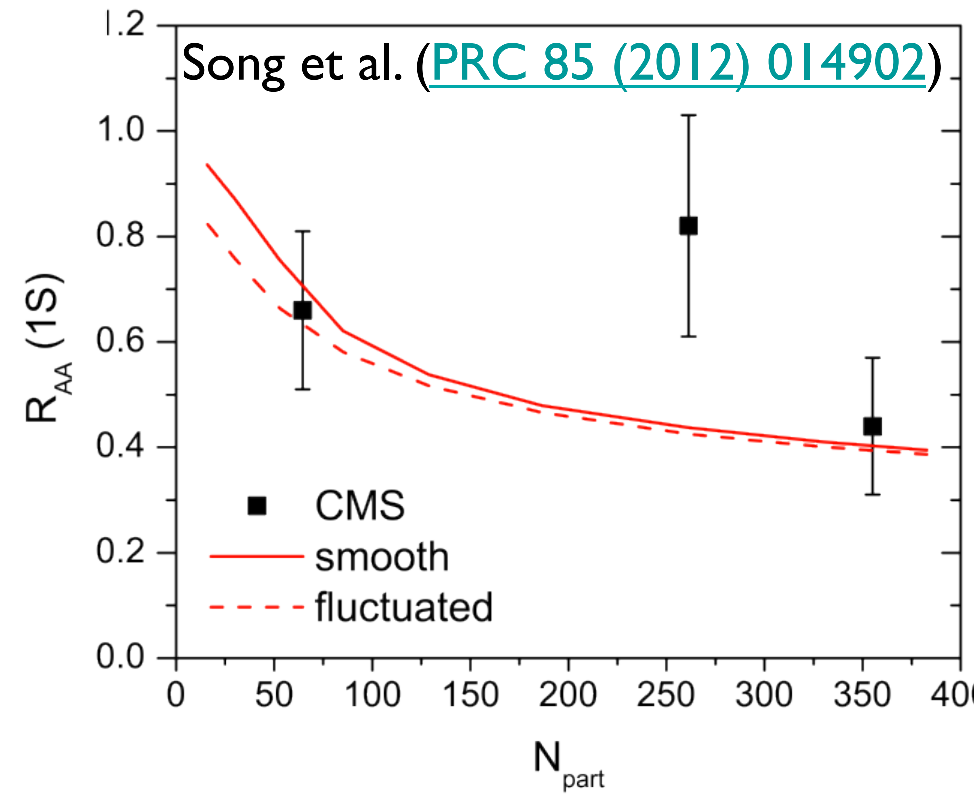
- Υ(1S) suppressed at low p_T
- No obvious rapidity dependence
- CMS: Υ(1S)
  - suppressed by factor ~2.2 in 0–10%
- STAR measures $$R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$$ (arXiv:1109.3891)
  - for CMS (0–100%): $$R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}}$$ $$= 0.63 \times \frac{1+0.24}{1+0.78} \approx 0.44$$

arXiv:1201.5069 (accepted to JHEP)

ϒ(1S) RAA



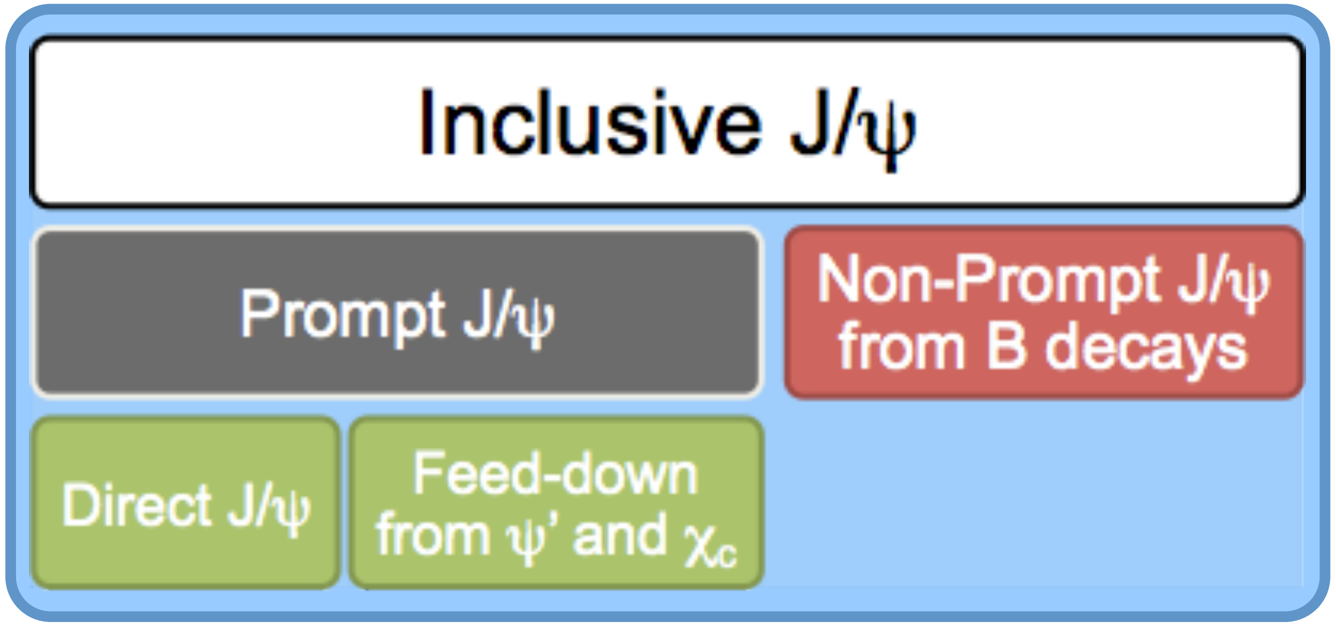


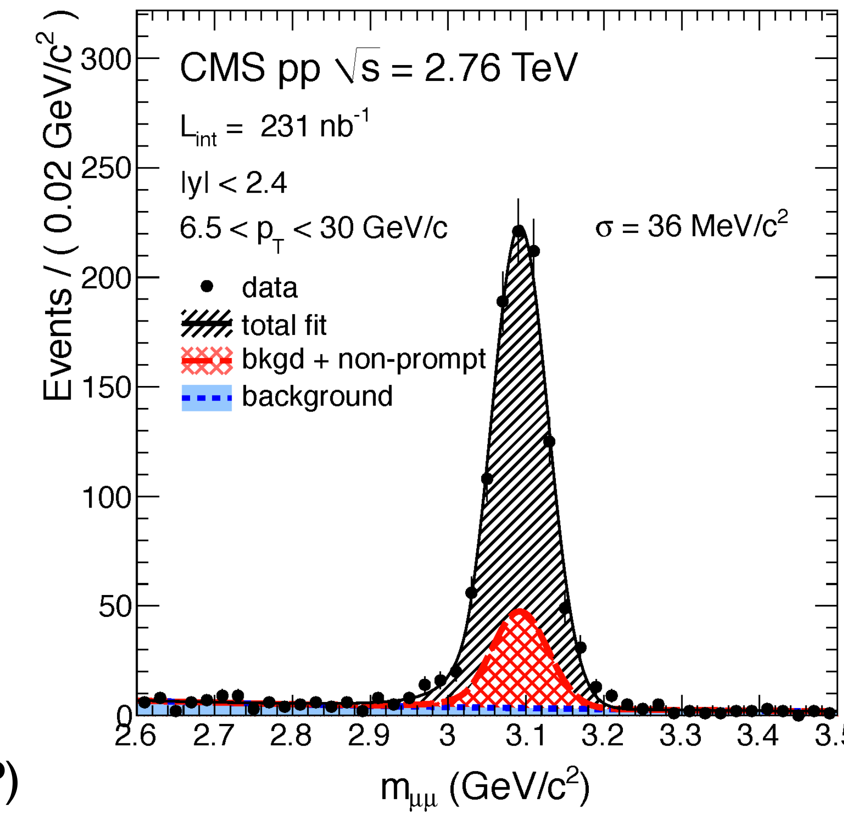


- ϒ(1S) suppressed at low p_T
- No obvious rapidity dependence
- A lot of activity on the theory side
  - Strickland (PRL 107 (2011) 132301)
  - Rapp et al. (arXiv:1111.6537)
  - Song et al. (PRC 85 (2012) 014902)
  - Brezinski et al. PLB 707 (2012) 534

arXiv:1201.5069
(accepted to JHEP)

J/ψ in pp at $\sqrt{s}$ = 2.76 TeV

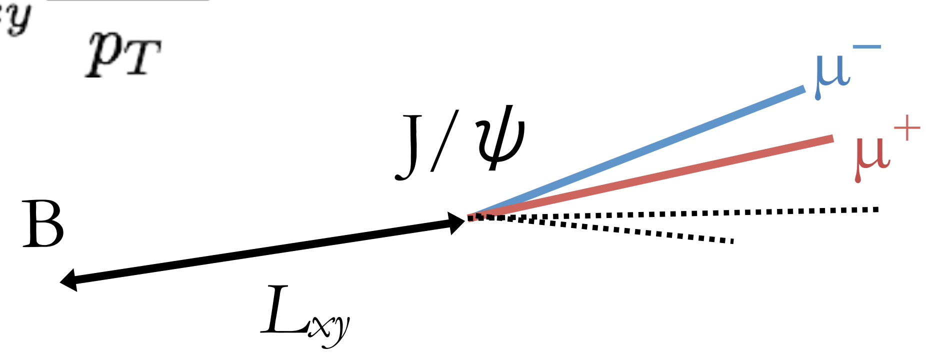


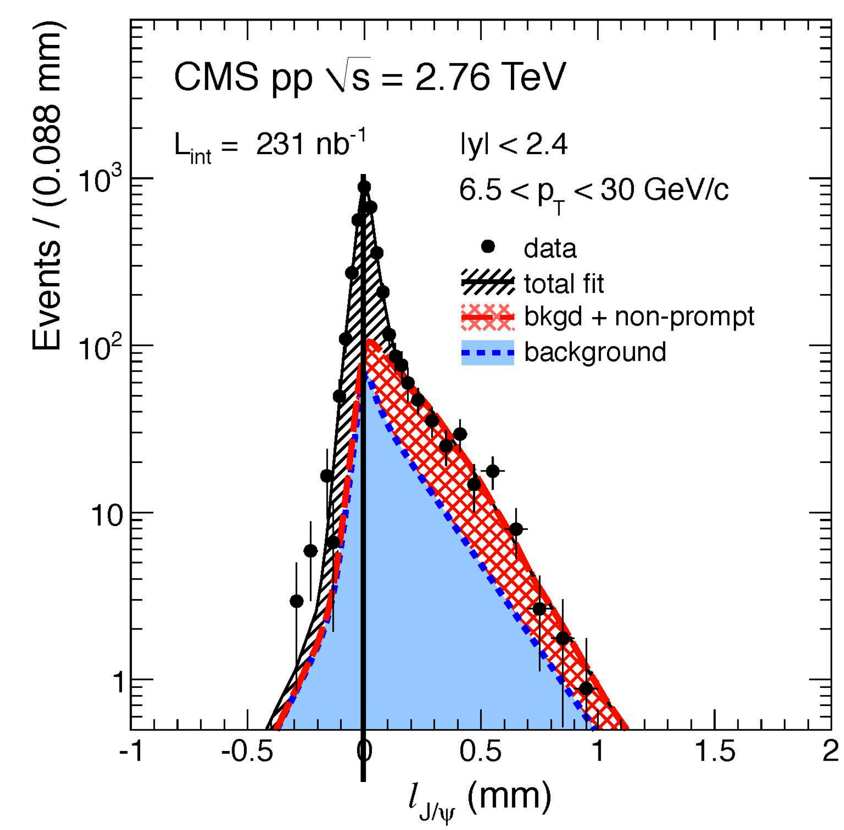


arXiv:1201.5069
(accepted to JHEP)

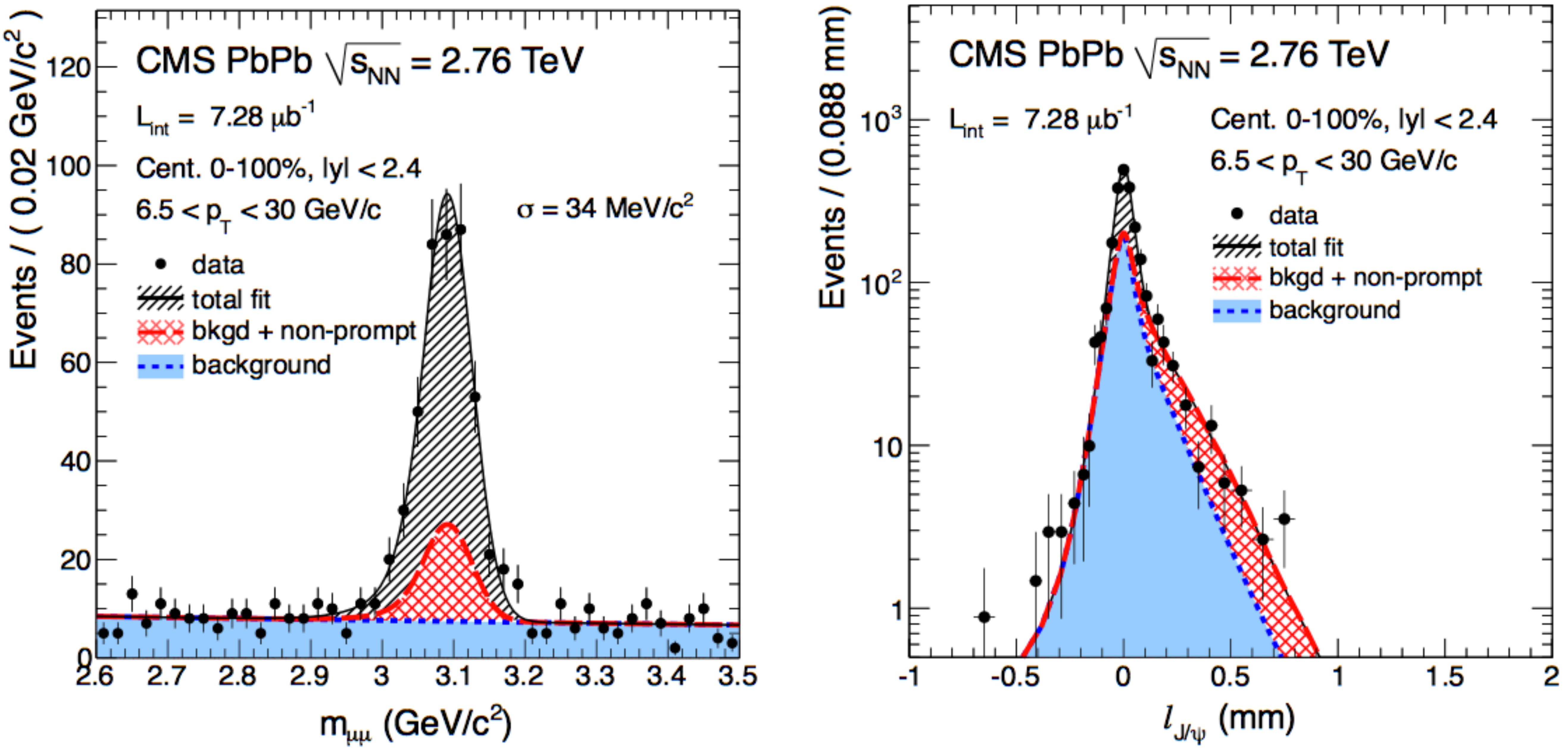
- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$





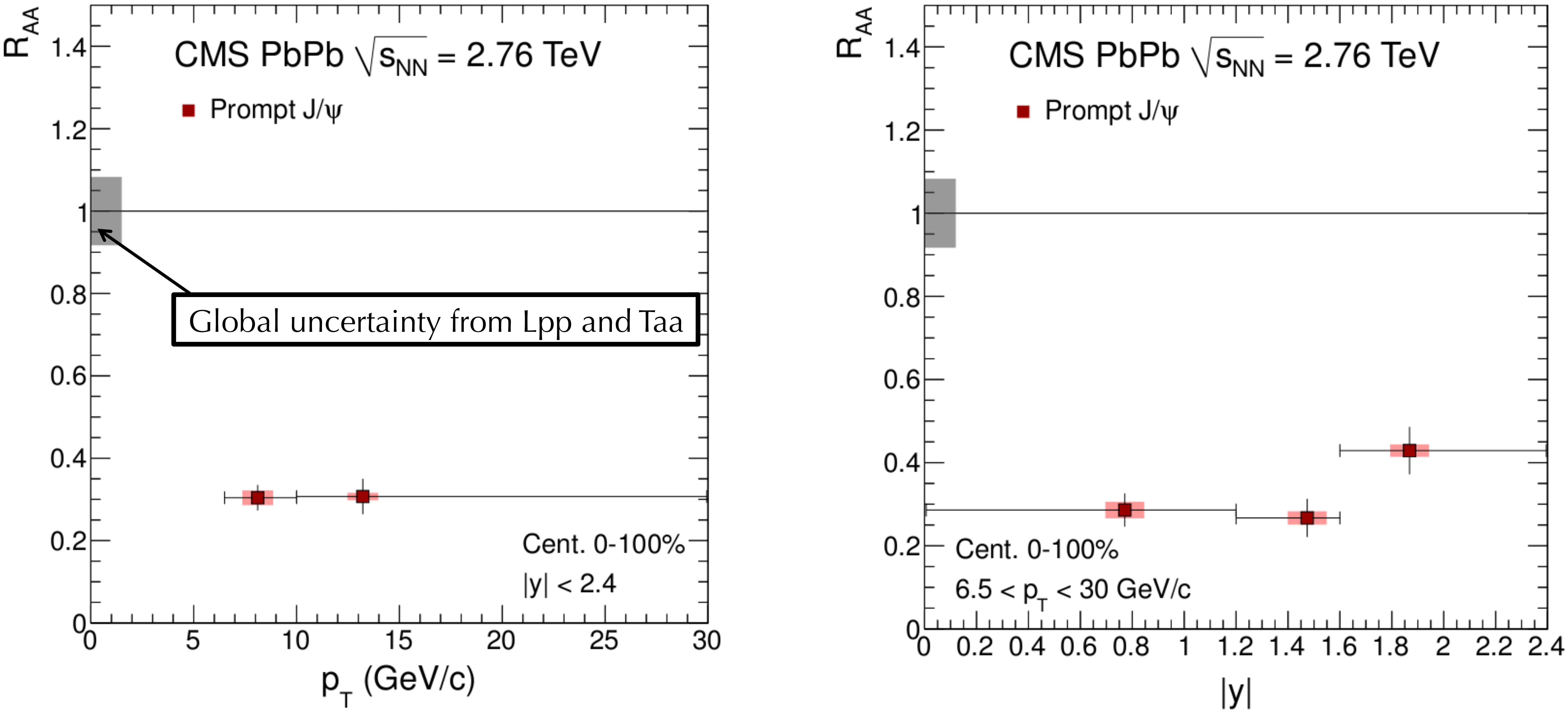
Prompt vs. non-prompt J/ψ in PbPb



- First time that prompt and non-prompt J/ψ have been separated in heavy ion collisions

arXiv:1201.5069
(accepted to JHEP)

Prompt J/ψ R_{AA} vs. p_T and y



- CMS: p_T > 6.5 GeV/c
  - Factor 3 suppression for p_T > 6.5 GeV/c and at y = 0
  - Trend to less suppression at forward rapidity

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}(\mathrm{cent})}$$

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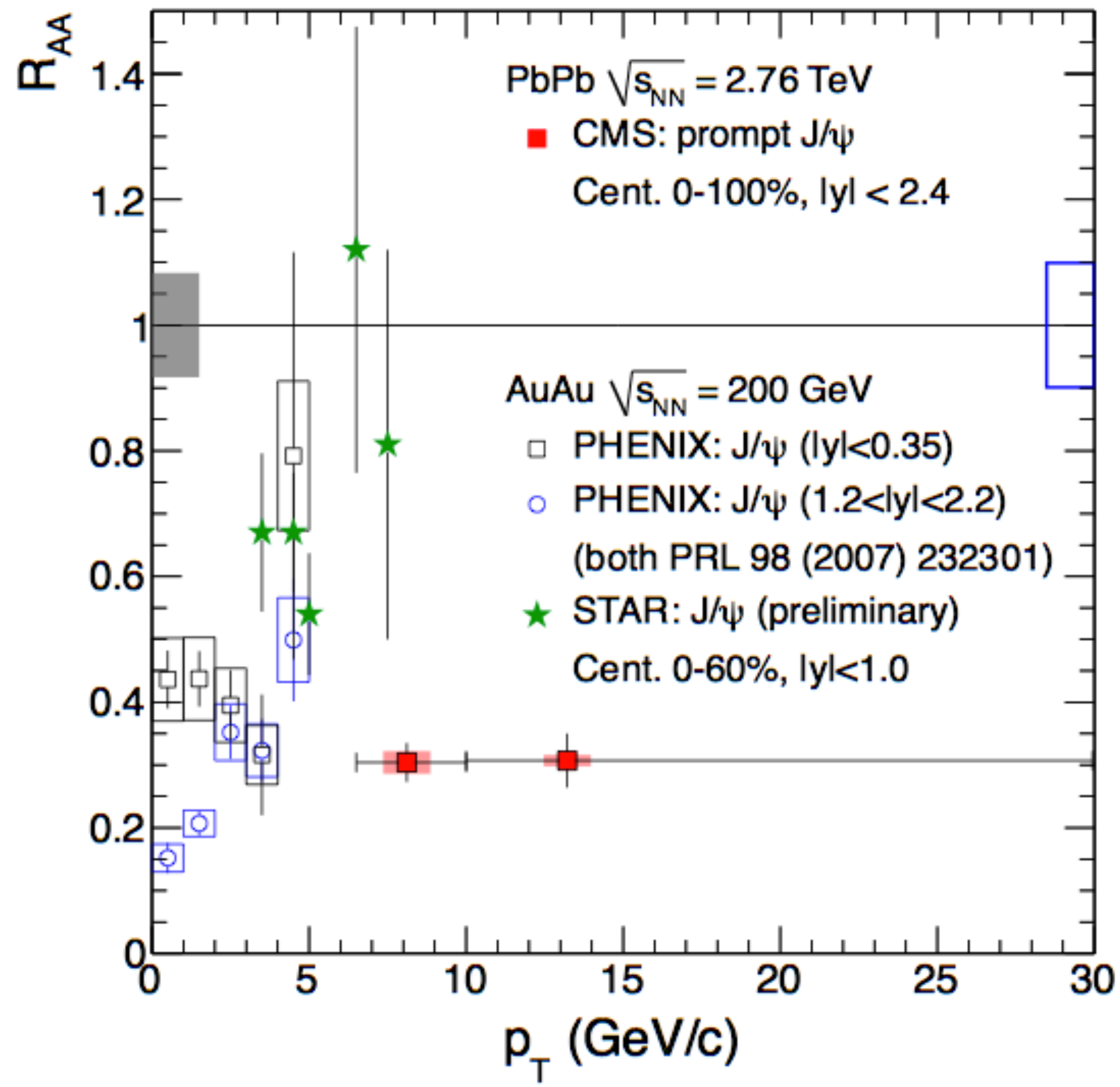
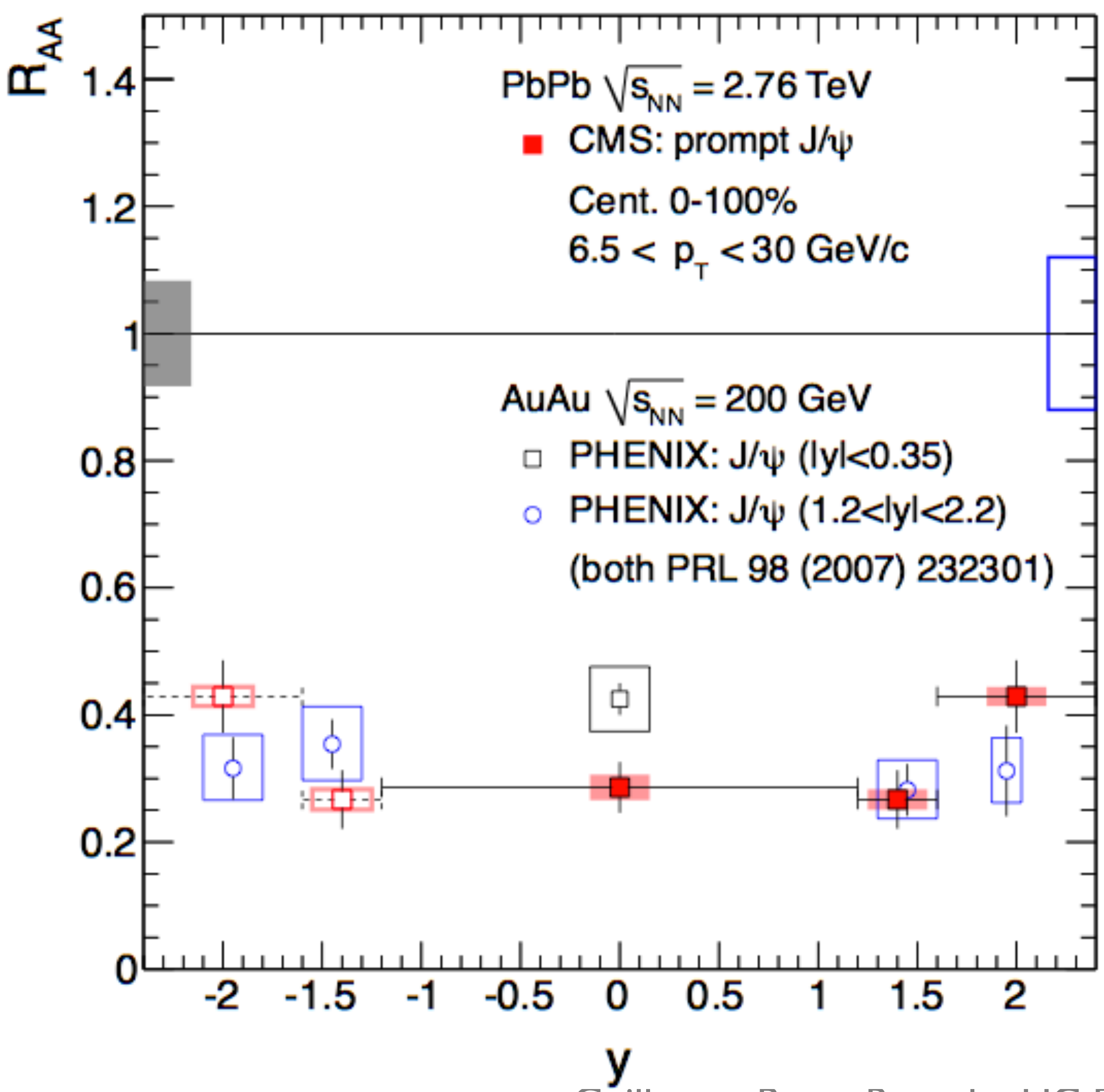
Prompt J/ψ R_{AA} vs. p_T and y

- CMS: p_T > 6.5 GeV/c
  - Factor 3 suppression for p_T > 6.5 GeV/c and at y = 0
  - Trend to less suppression at forward rapidity
- STAR: no suppression at high p_T
- PHENIX: lower p_T
  - opposite rapidity dependence





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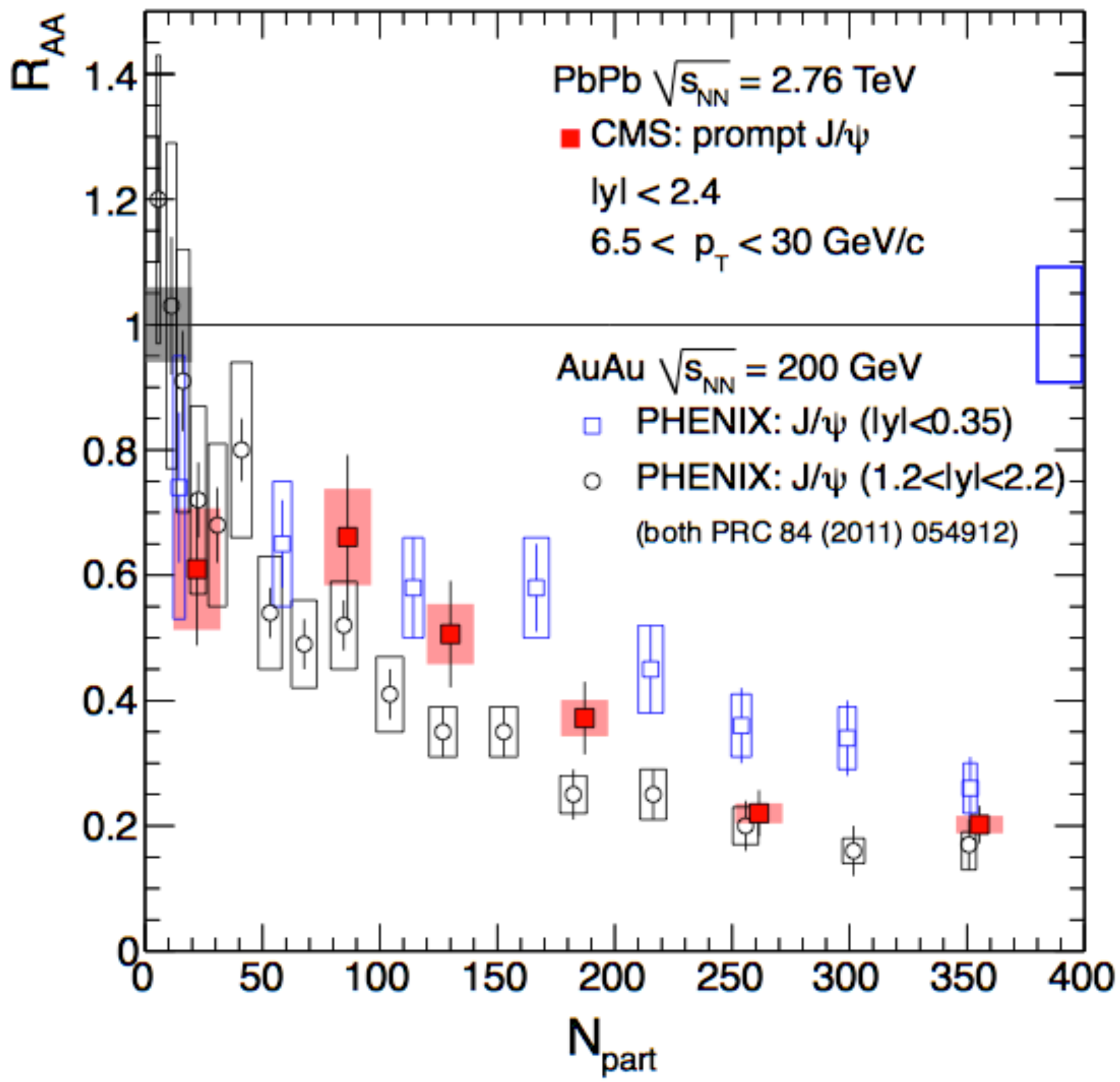
Prompt J/ψ R_{AA} vs. centrality



- Prompt J/ψ :
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor ~1.6
- Similar suppression seen by PHENIX
  - though at lower p_T

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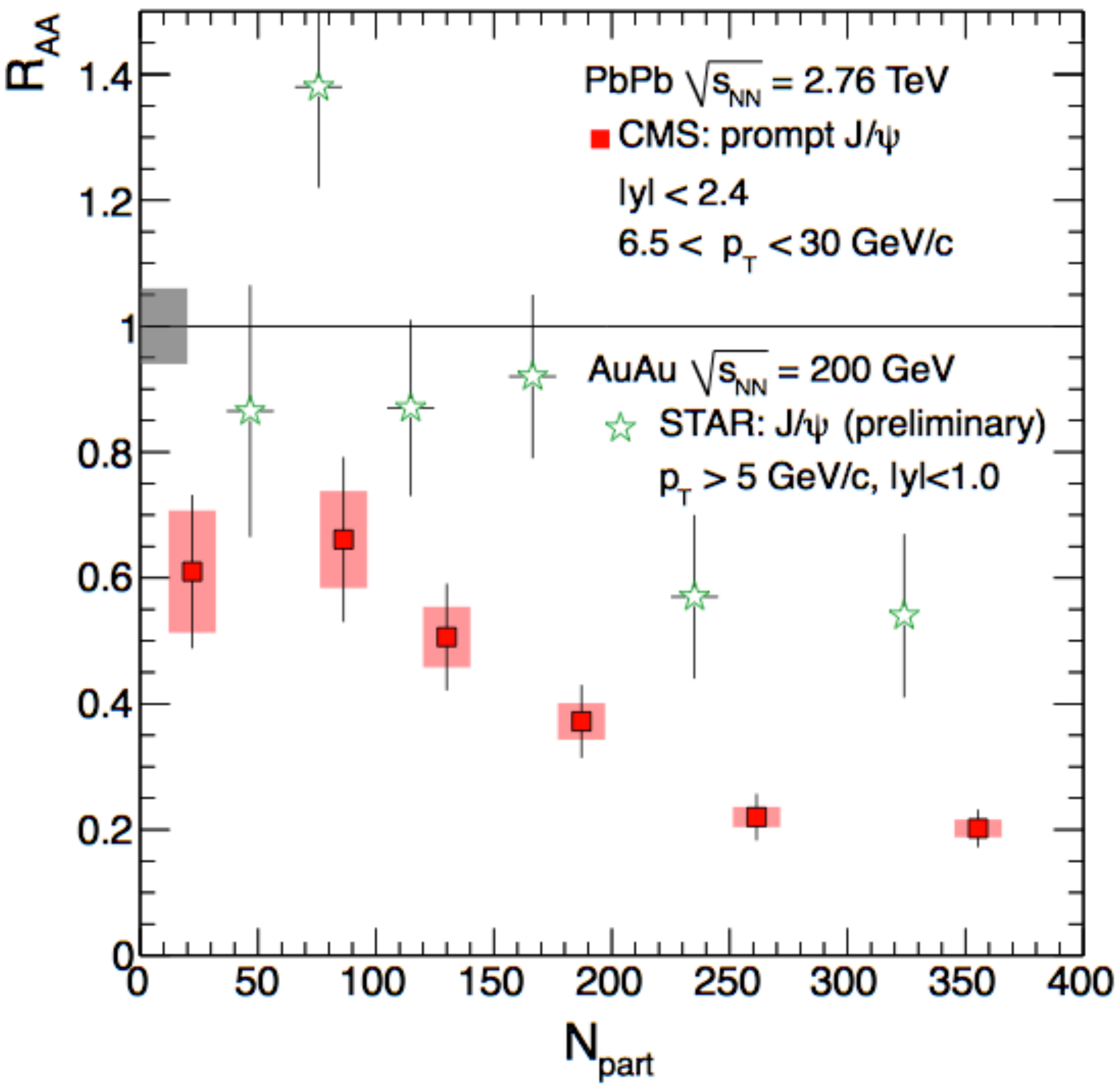
Prompt J/ψ R_{AA} vs. centrality



- STAR measures less suppression at high p_T

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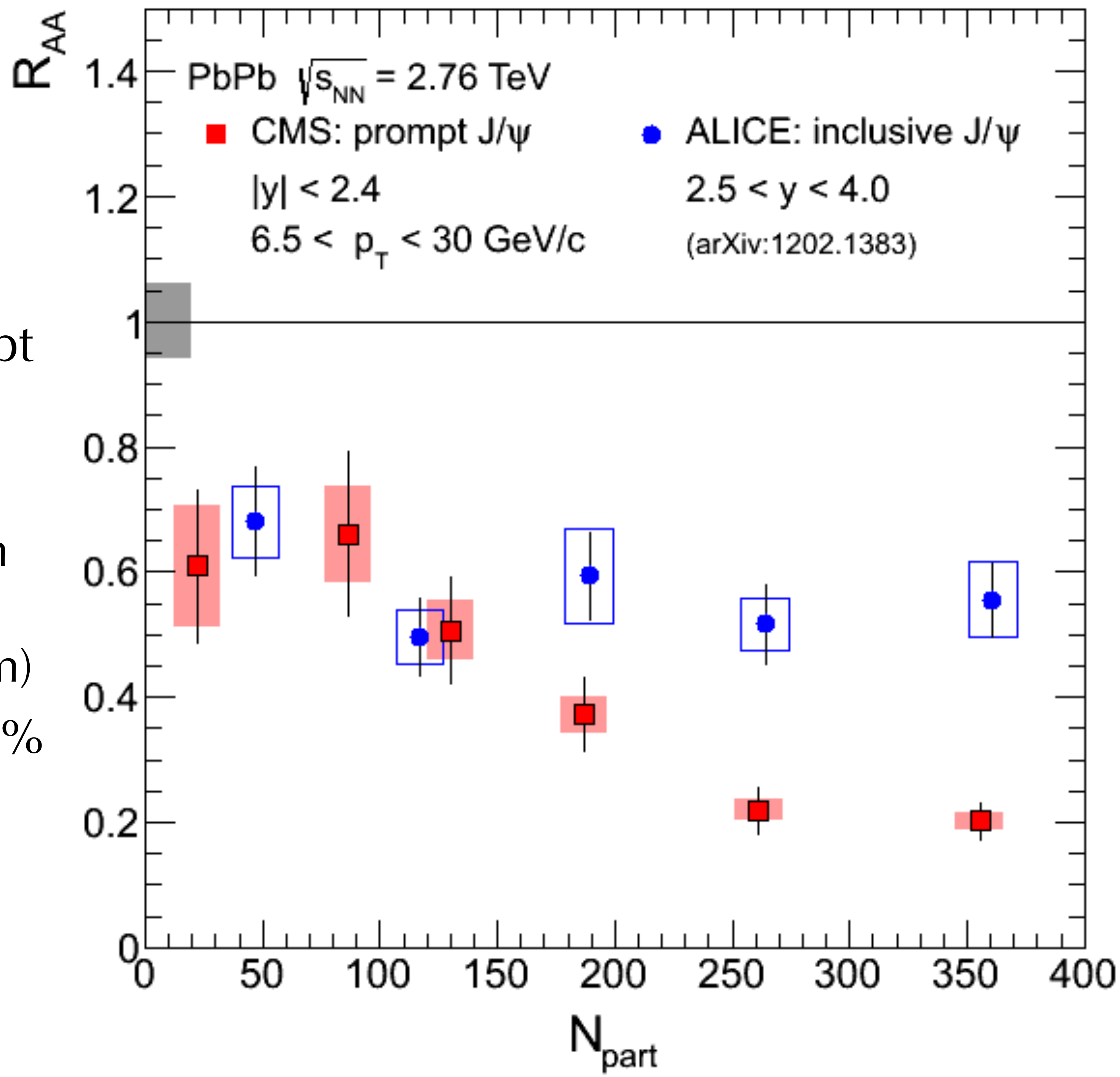
(accepted to JHEP)

Prompt J/ψ R_{AA} vs. centrality

- ALICE: inclusive J/ψ, $p_T > 0$ GeV/c,
- Centrality 0–80%
  - $R_{AA} = 0.49 \pm 0.03 \pm 0.11$ (Pillot, QM2011)
- Careful when comparing R_{AA} of prompt J/ψ (CMS) and inclusive J/ψ (ALICE)
  - In pp at low p_T: ~10% b-fraction
  - From RHIC we know that open charm cross section is unmodified (can assume the same for open bottom)
  - non-prompt J/ψ could shift R_{AA} by 10%



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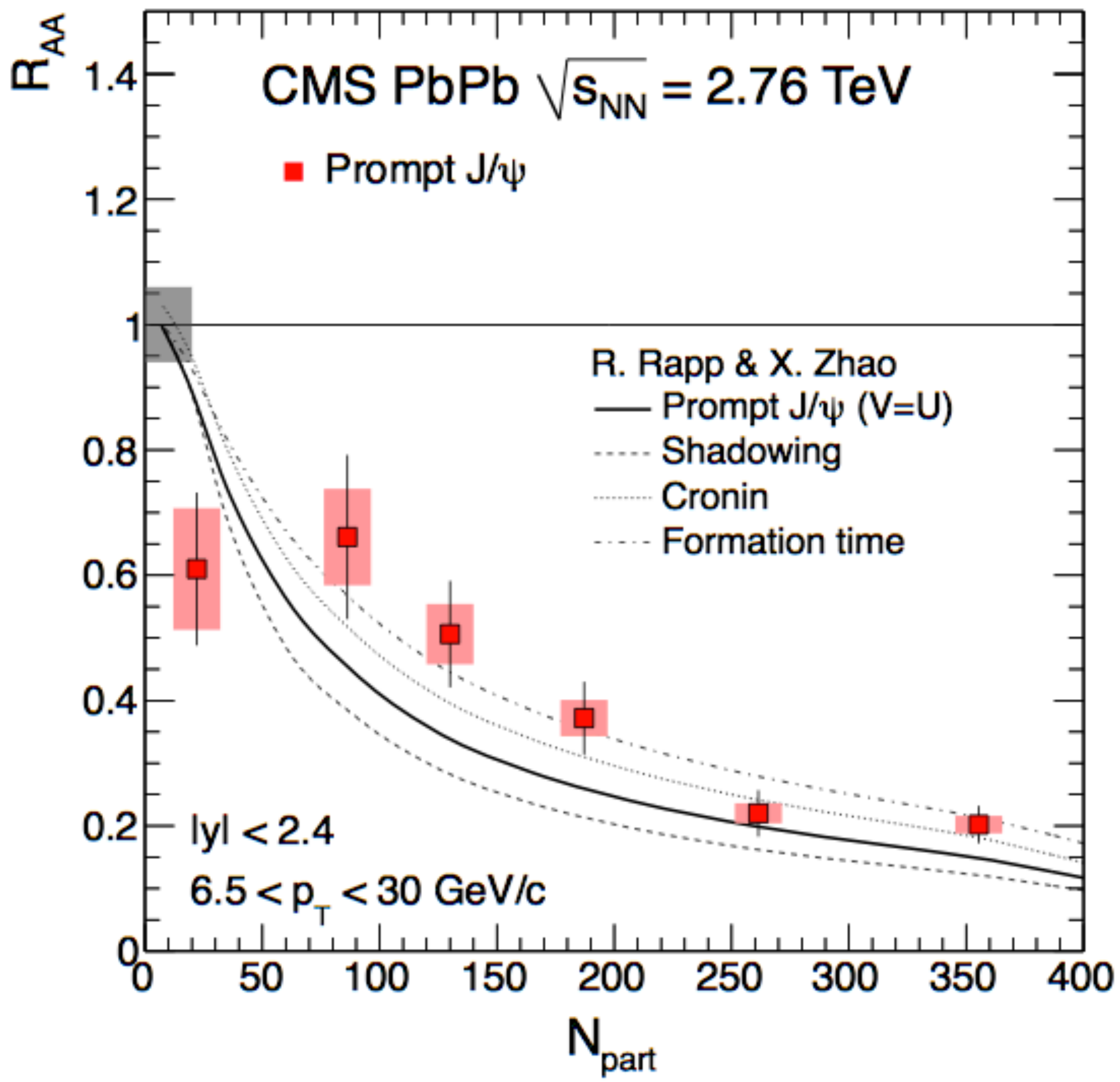
Prompt J/ψ R_{AA} vs. centrality

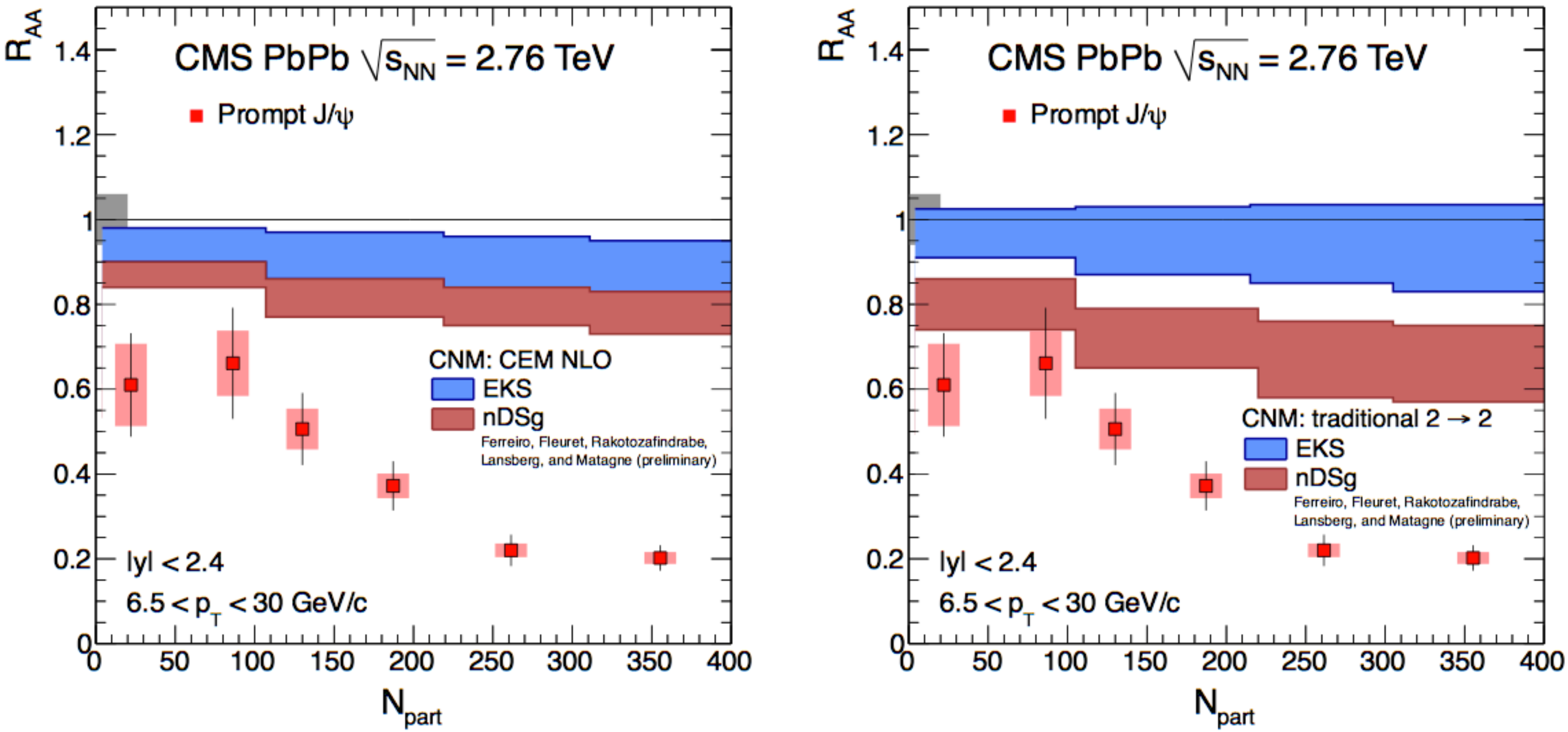


- Prompt J/ψ :
  - Most Central suppressed by factor 5 with respect to pp
  - Most Peripheral suppressed by factor ~1.6

- Kinetic Rate Equation Approch
  - Incorporates various effects.
  - Assumes strong binding scenario
  - Recombination negligible for p_T>6.5 GeV/c
  - Predict large suppression of primordial charmonia (~10 for central Pb-Pb collisions)

Zhao & Rapp, NPA 859 (2011) 114

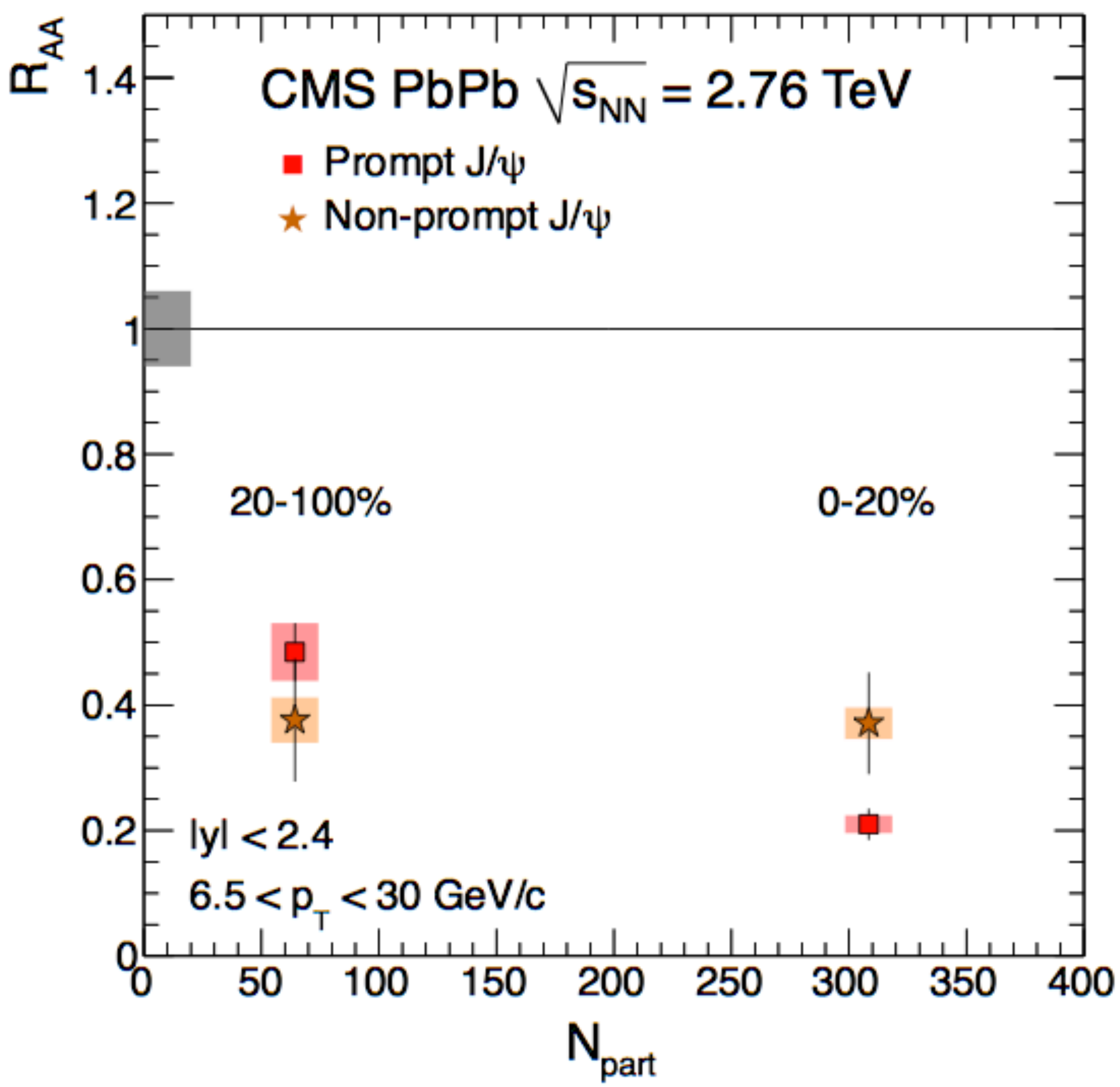
Prompt J/ψ: Cold Nuclear Matter effects?

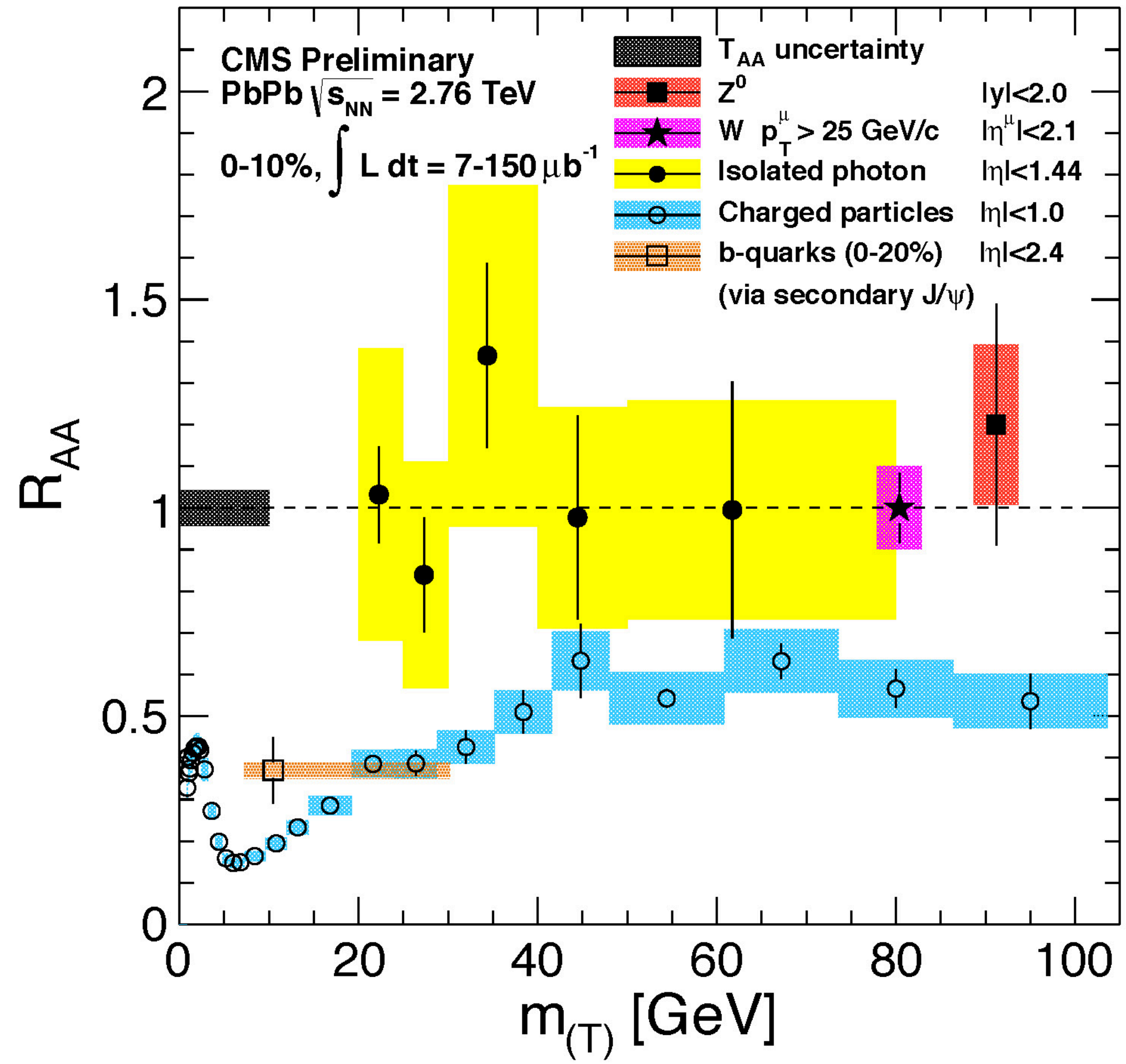


- Work in progress to estimate (anti)shadowing contributions
  - Two different nuclear parton distribution functions.
  - Traditional 2 -> 2 calculations include kT smearing.
  - Suppression beyond the reach of CNM effects.

Ferreiro et al. (preliminary)

Open heavy-flavour: Non-Prompt J/ψ R_{AA}

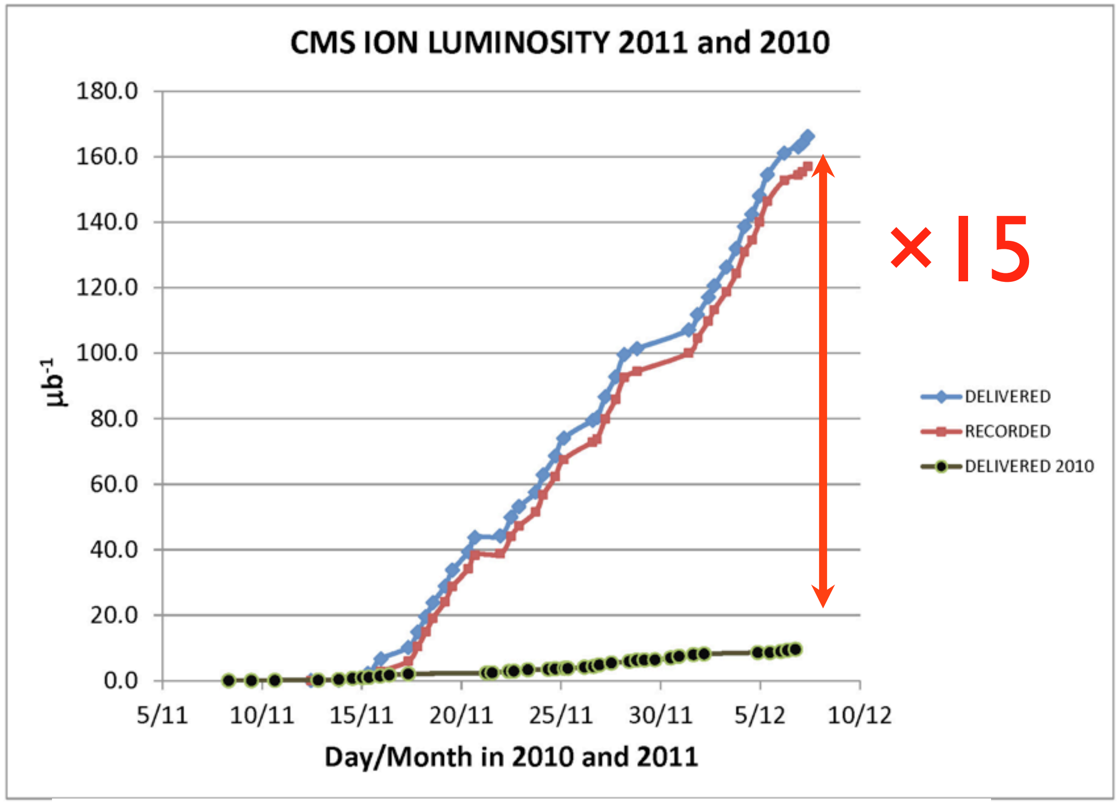




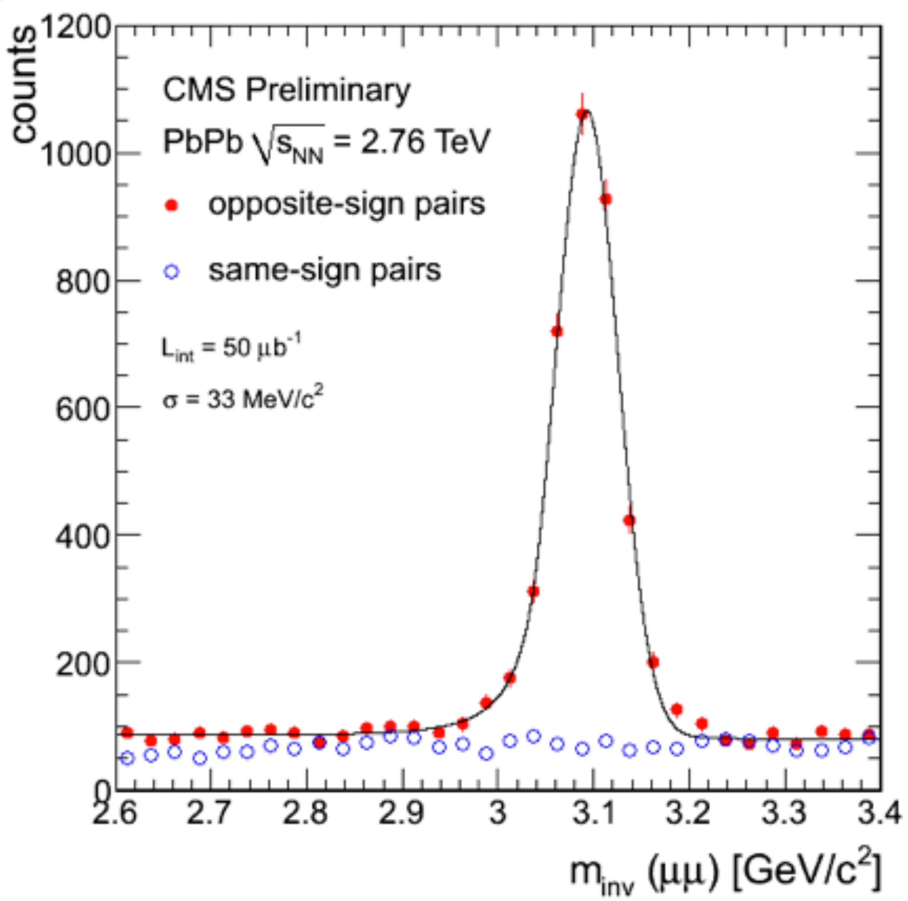
- Suppression of non-prompt J/ψ observed in min. bias and central PbPb collisions
  - First indications of high-p_T b-quark quenching!

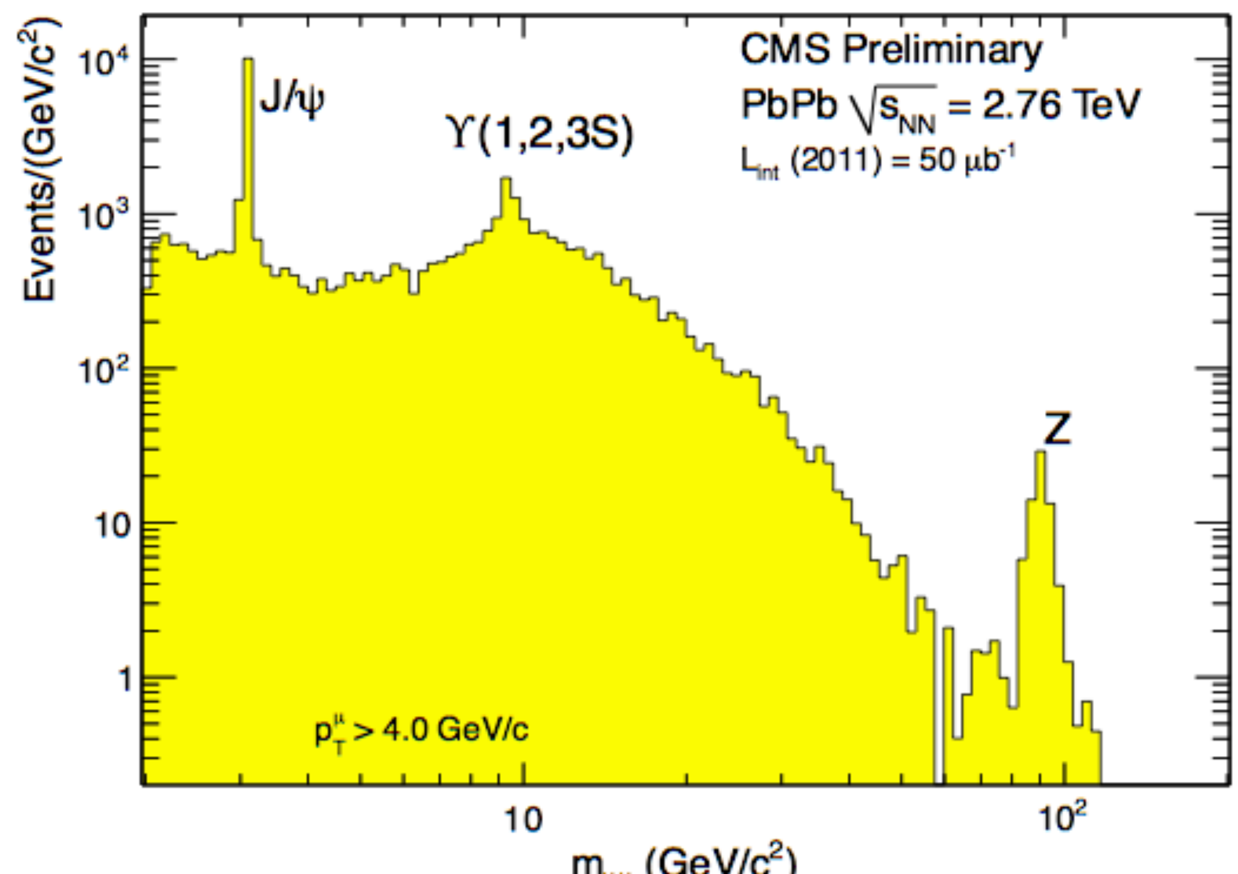
arXiv:1201.5069
(accepted to JHEP)

Outlook

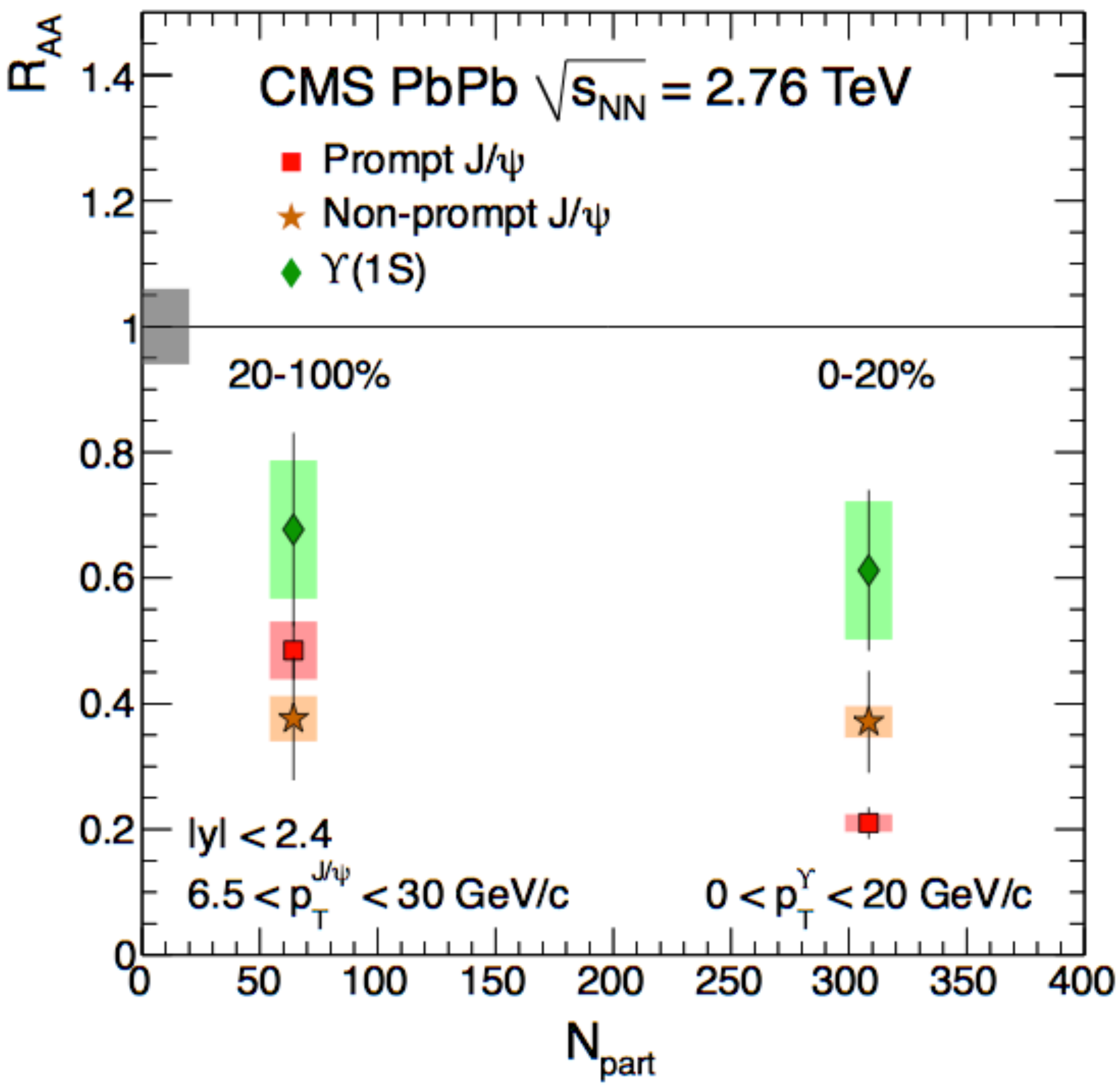


- Recorded 150 μb^{-1} in 2011
  - including a double muon trigger without p_T cut (muon p_T reach limited only by acceptance)
- Will be able to study quarkonia in PbPb collisions in much more detail
  - Double differential measurements of prompt J/ψ R_{AA}
  - Precise measurement of excited Υ states double ratio
  - R_{AA} of Υ(nS) states
  - Map centrality and p_T dependence of b-quark energy loss with non-prompt J/ψ



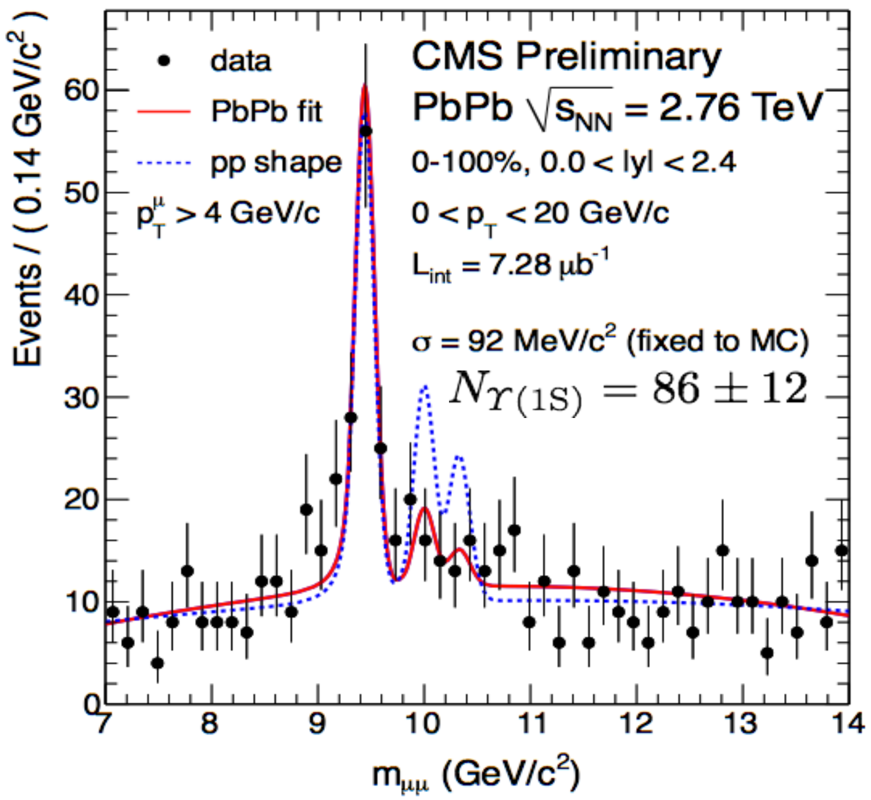


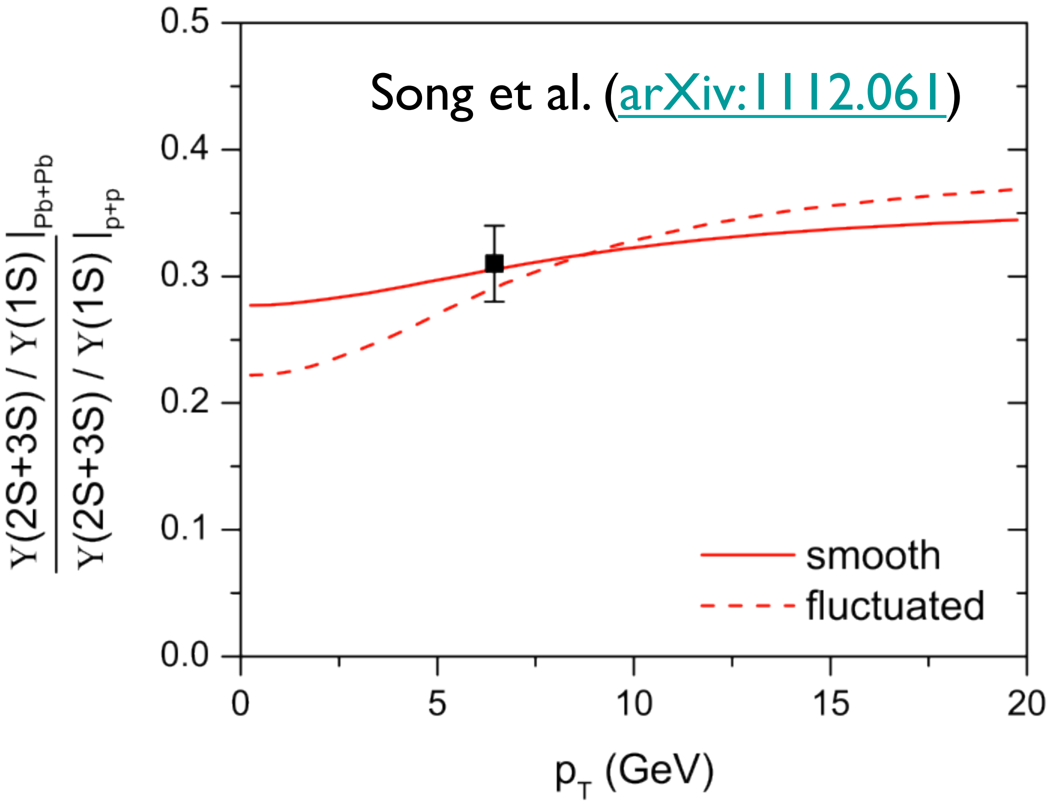
Summary

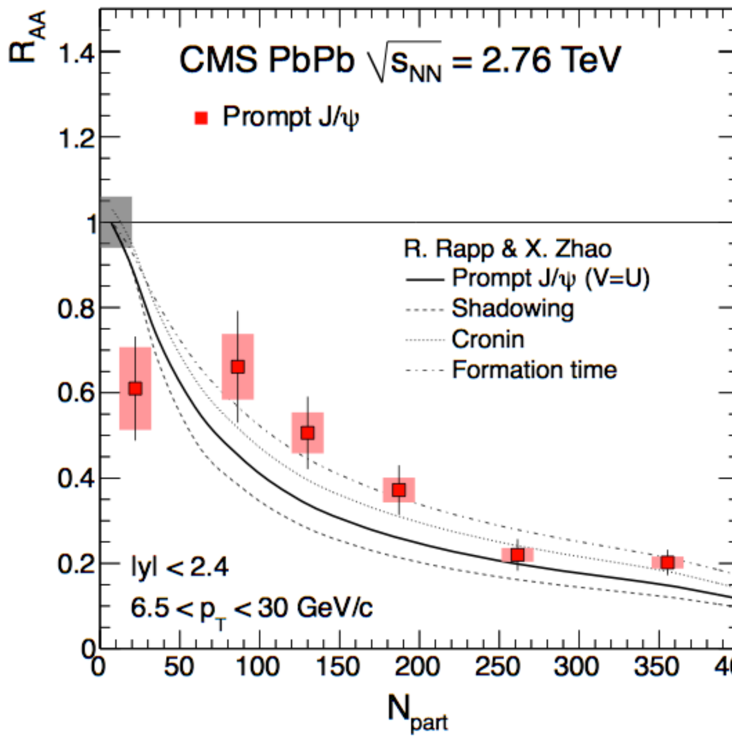


- In PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- Prompt J/ψ suppressed
- Υ(2S+3S) suppressed relative to Υ(1S)
  - Observed Υ(1S) suppression consistent with melting of excited states only
- J/ψ from B decays suppressed

Υ(2S+3S) Suppression and J/ψ Questions







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$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

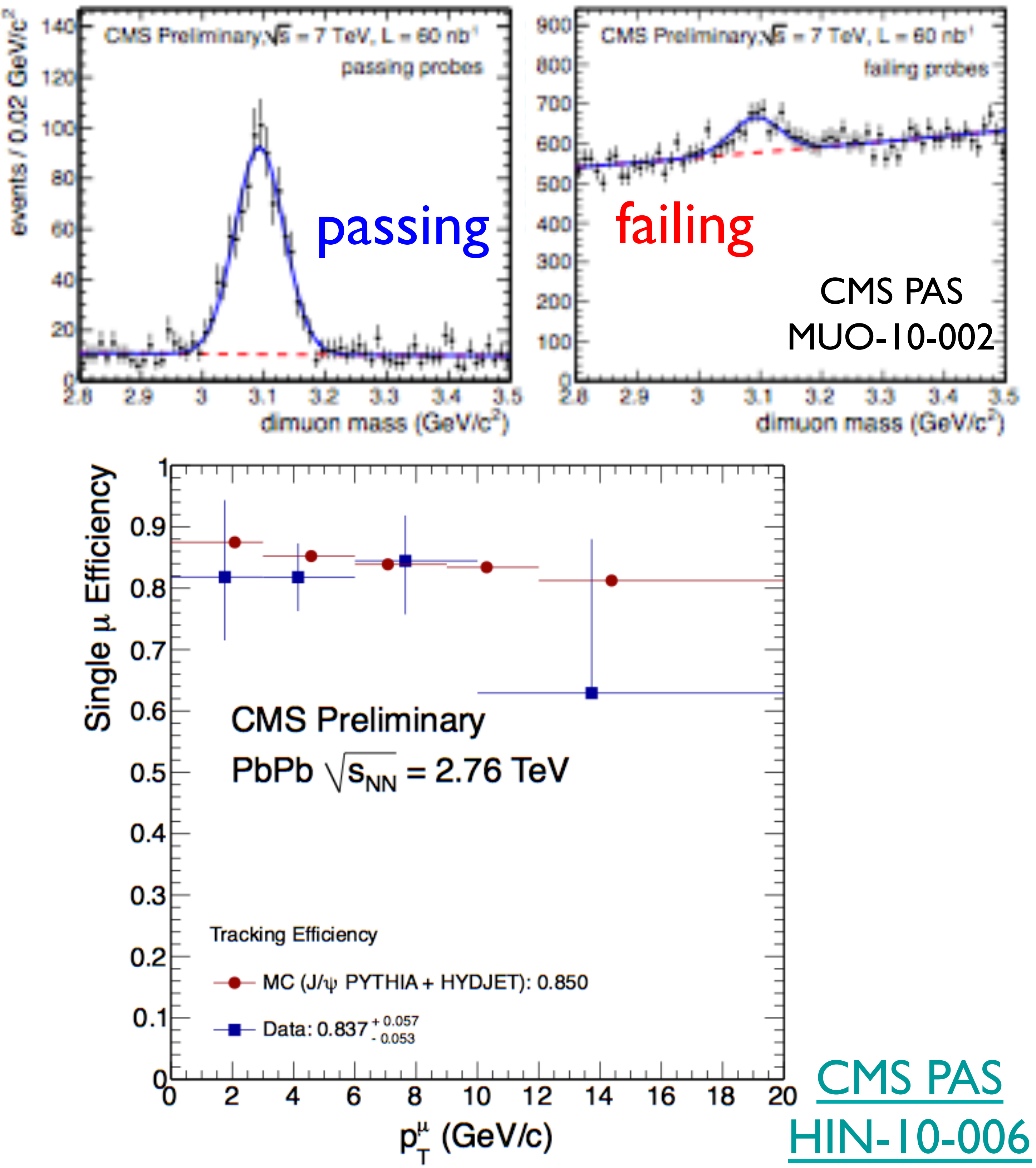
- With 2011 data (For Υ(1S+2S+3S)) :
  - Confirm suppression of excited states with higher precision
  - Measure double ratio as a function of centrality, p_T…
  - is there a centrality dependence of the double ratio?

(For J/ψ)

- out to which pT do J/psi remain suppressed?
- does J/psi flow?

Backup

Tag & Probe

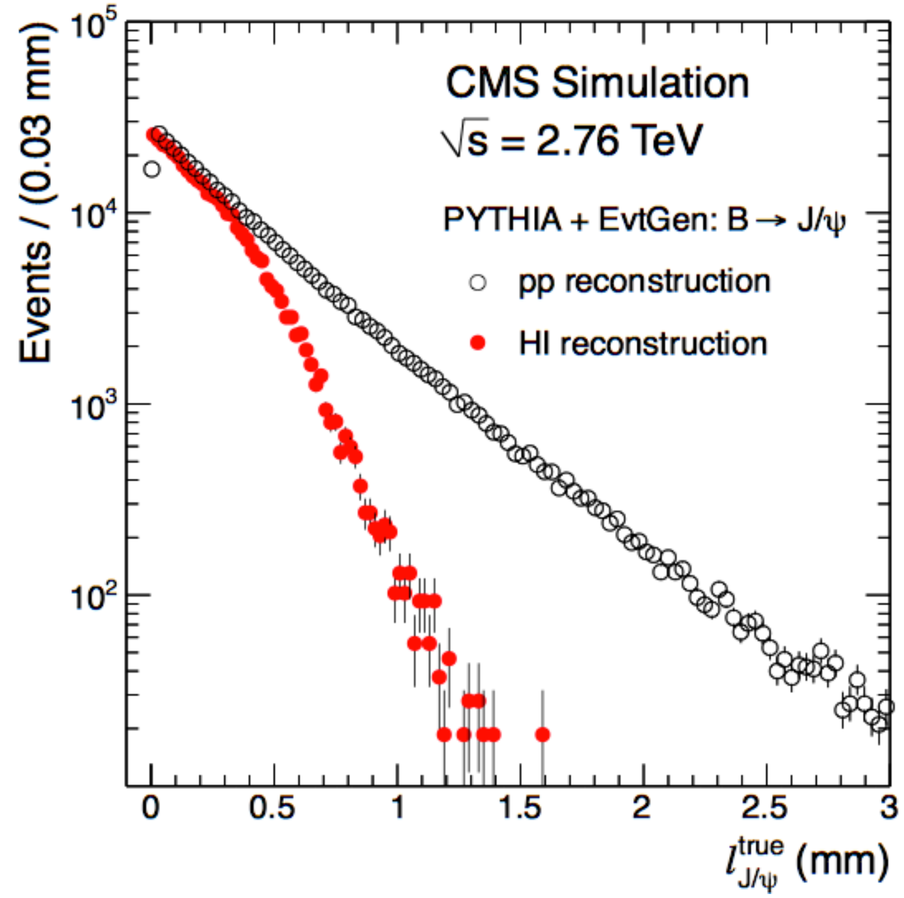


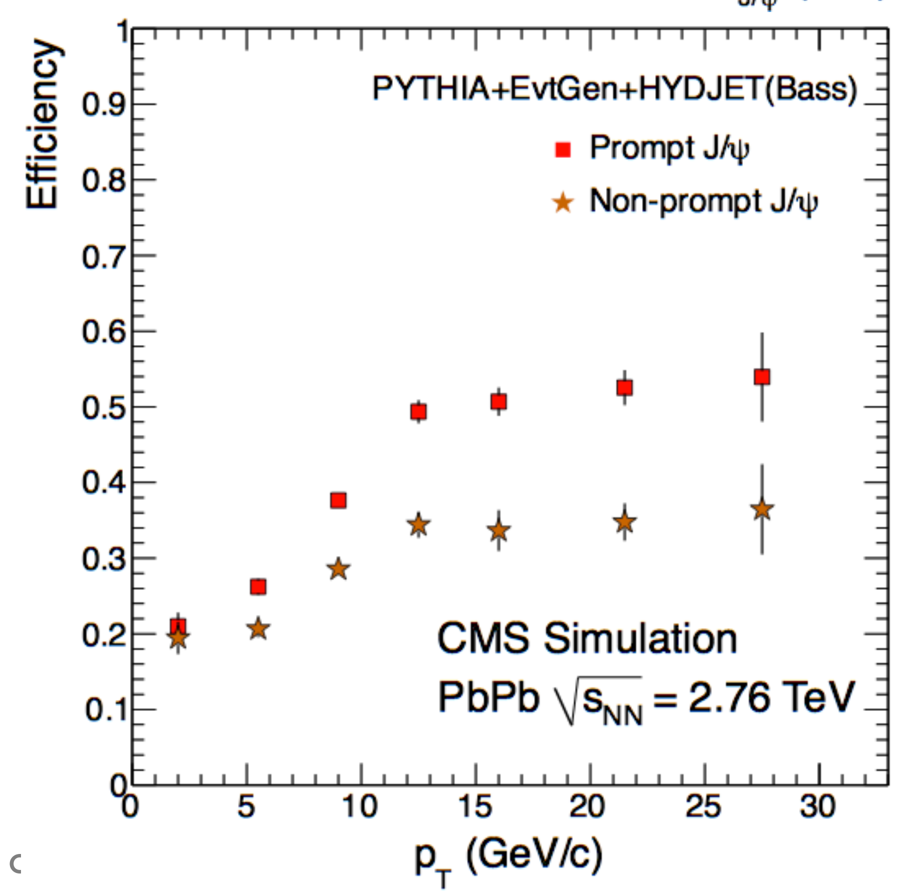
CMS PAS HIN-10-006

- Tracking efficiency:
- Tag: high quality muon
- Probe: track in the muon station
- Passing Probe:
  - Probe that is also reconstructed as global muon (i.e. with a track in the Si-tracker)
- Reconstruct J/ψ peak in passing probe-tag pairs and in failing probe-tag pairs
- Simultaneous fit to passing and failing probes allows us to measure the efficiency of the inner track reconstruction
- Agreement within stat. uncertainty of data → 14% systematic uncertainty on data/MC agreement
  - dominant systematic uncertainties on cross section results in PbPb

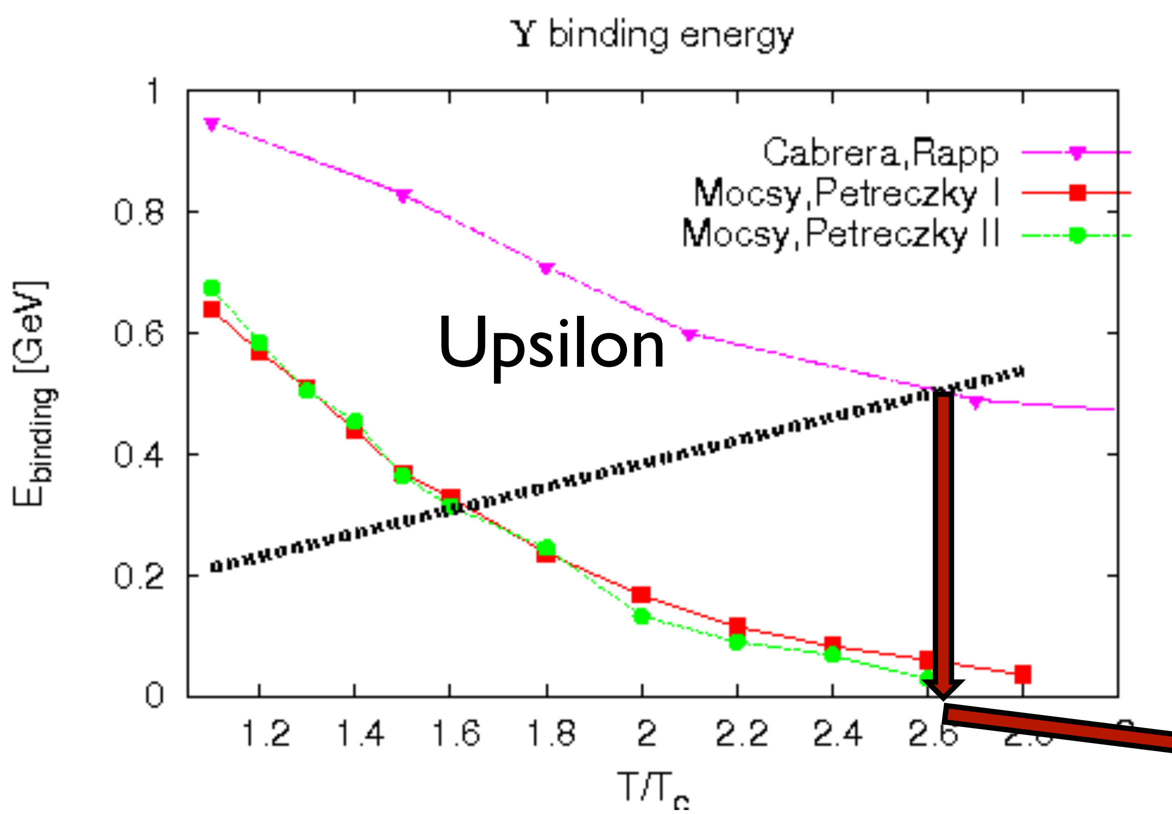
J/ψ in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

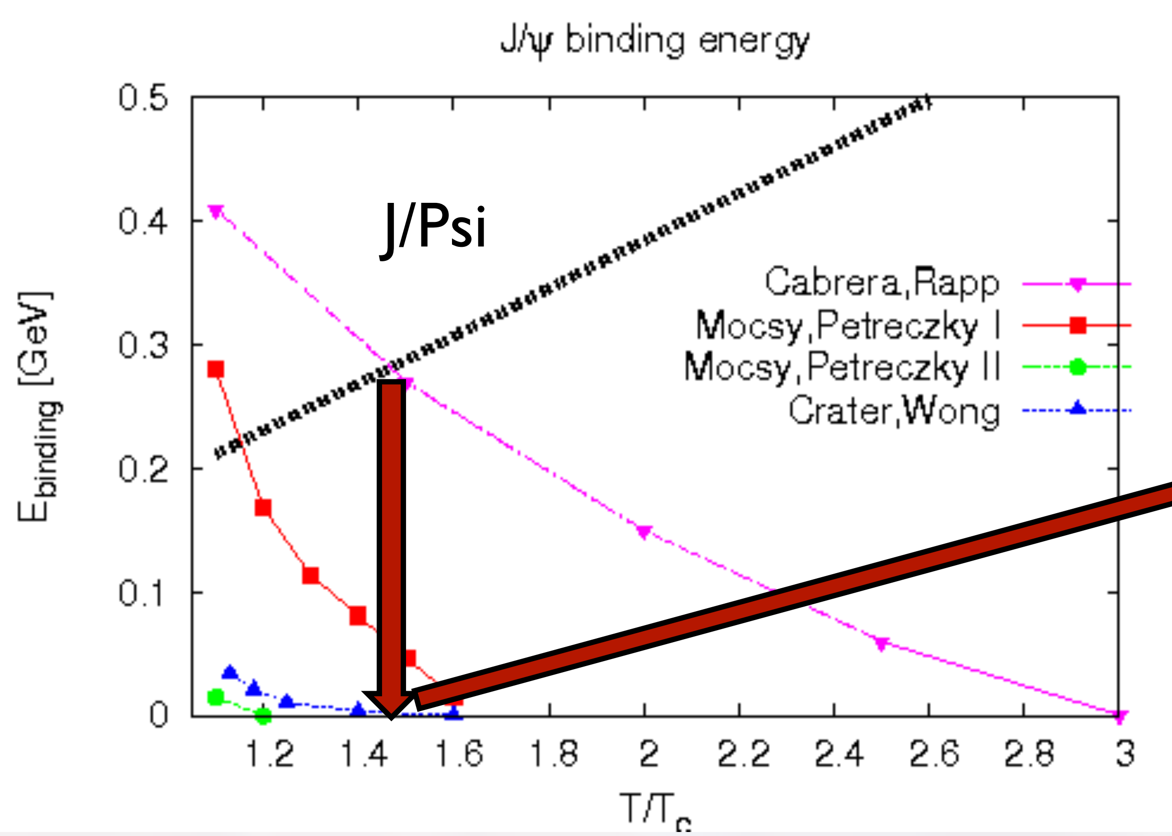
- Separate prompt & non-prompt J/ψ
- HI tracking algorithm uses vertex constraint
  - Smaller efficiency for non-prompt than for prompt J/ψ
  - Effect increases with p_T
- Efficiencies from Monte Carlo
  - Simulate signal with "realistic" PYTHIA
  - Embed signal in min. bias event simulated with HYDJET (also in data)
  - Validated MC by comparing efficiencies measured with "Tag & Probe" in MC and data





Sequential Melting

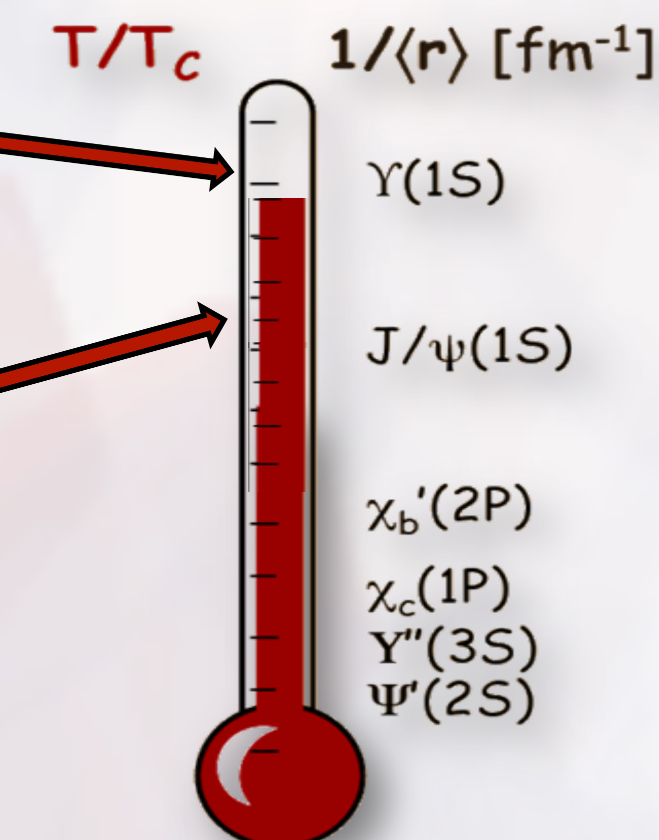




- Sequential Melting due to the Debye screening.
- Helps quantify medium properties (temperature)

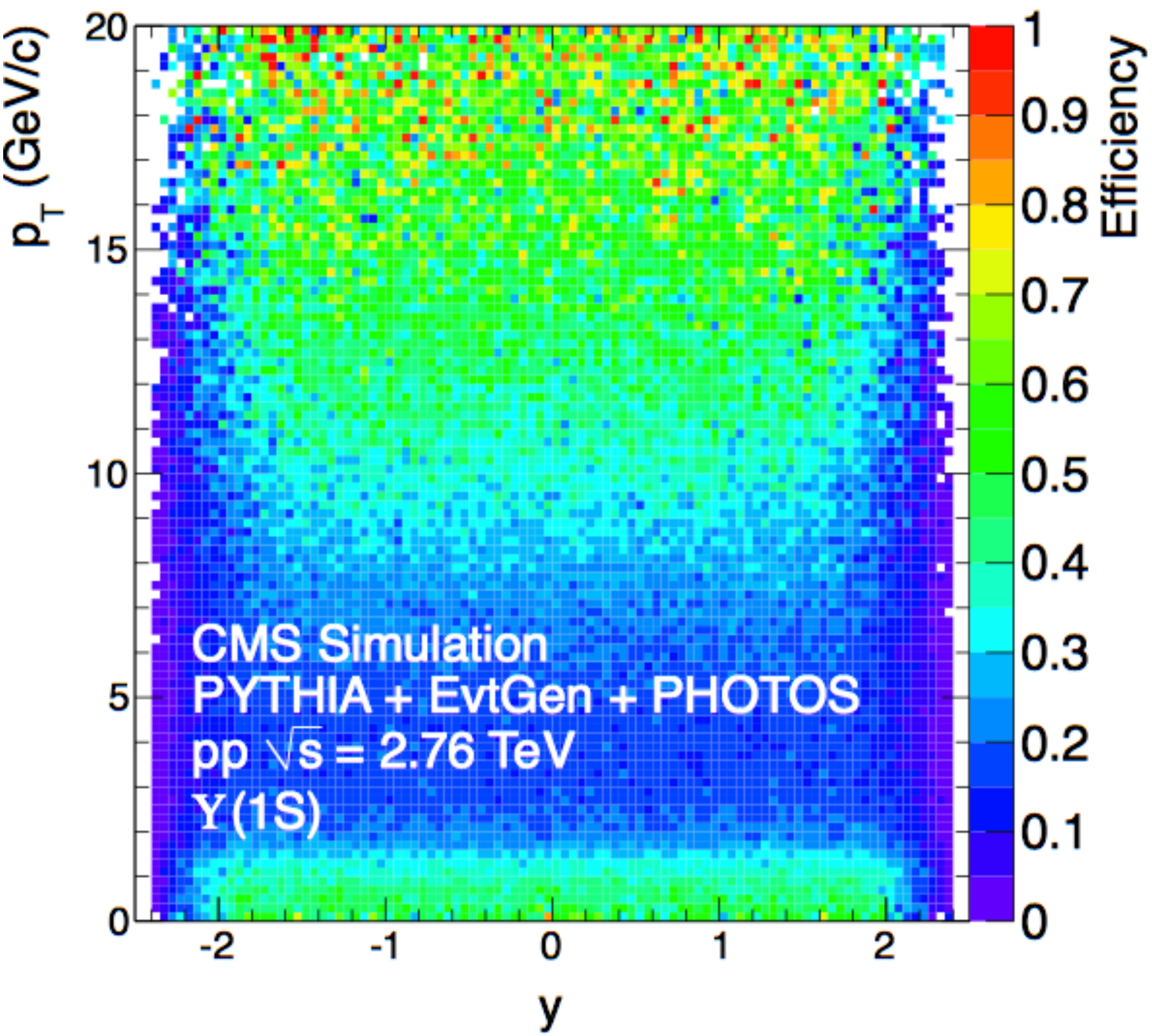
A.Mocsy arXiv:0811.0337

When does it dissociate?

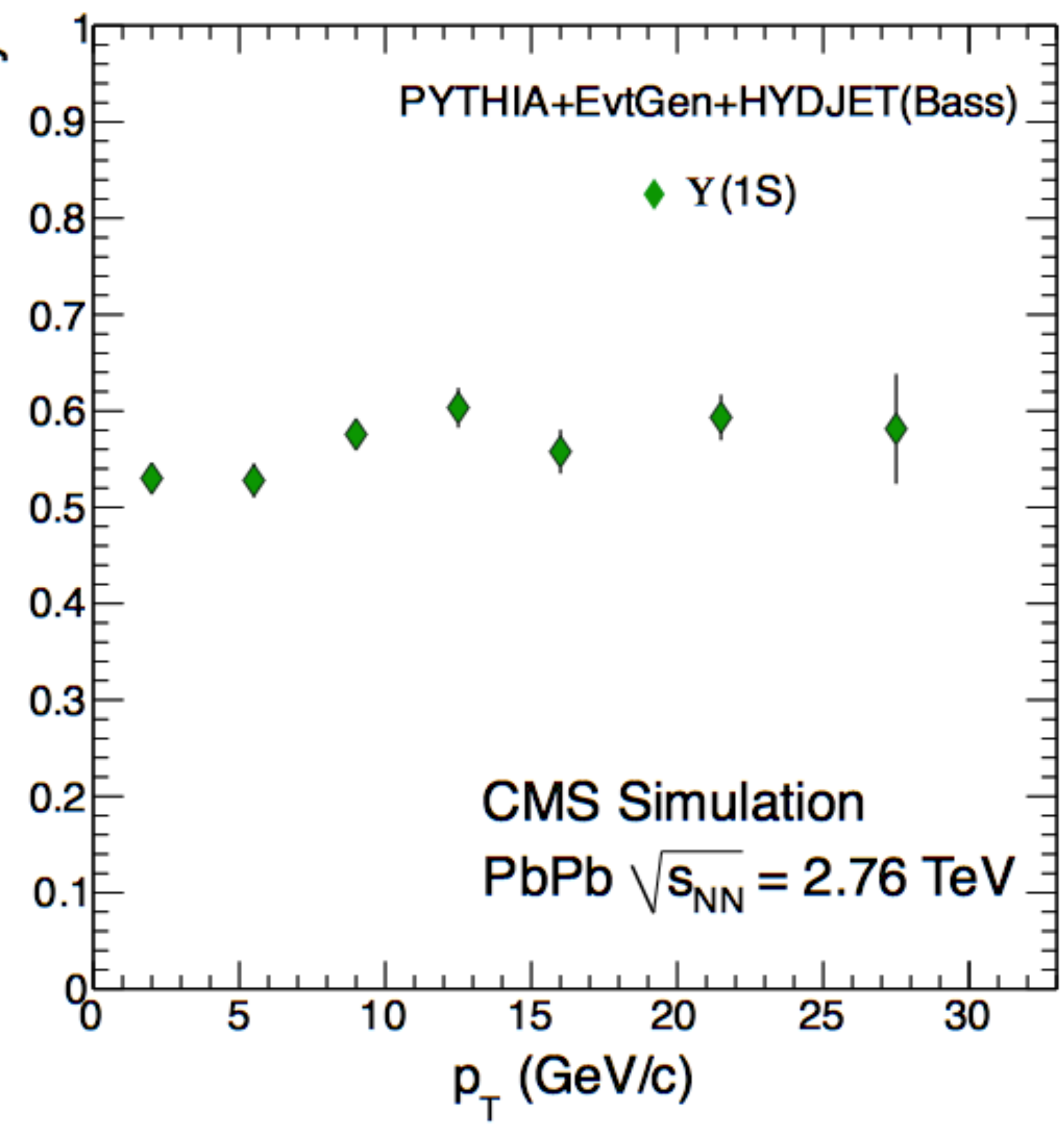


Υ(1S) Acceptance and Efficiency

Acceptance



Efficiency



- Efficiencies from Monte Carlo
  - Validated with data driven method (Tag & Probe)
- Acceptance to p_T = 0 GeV/c

J/ψ in pp at $\sqrt{s}$ = 7 TeV

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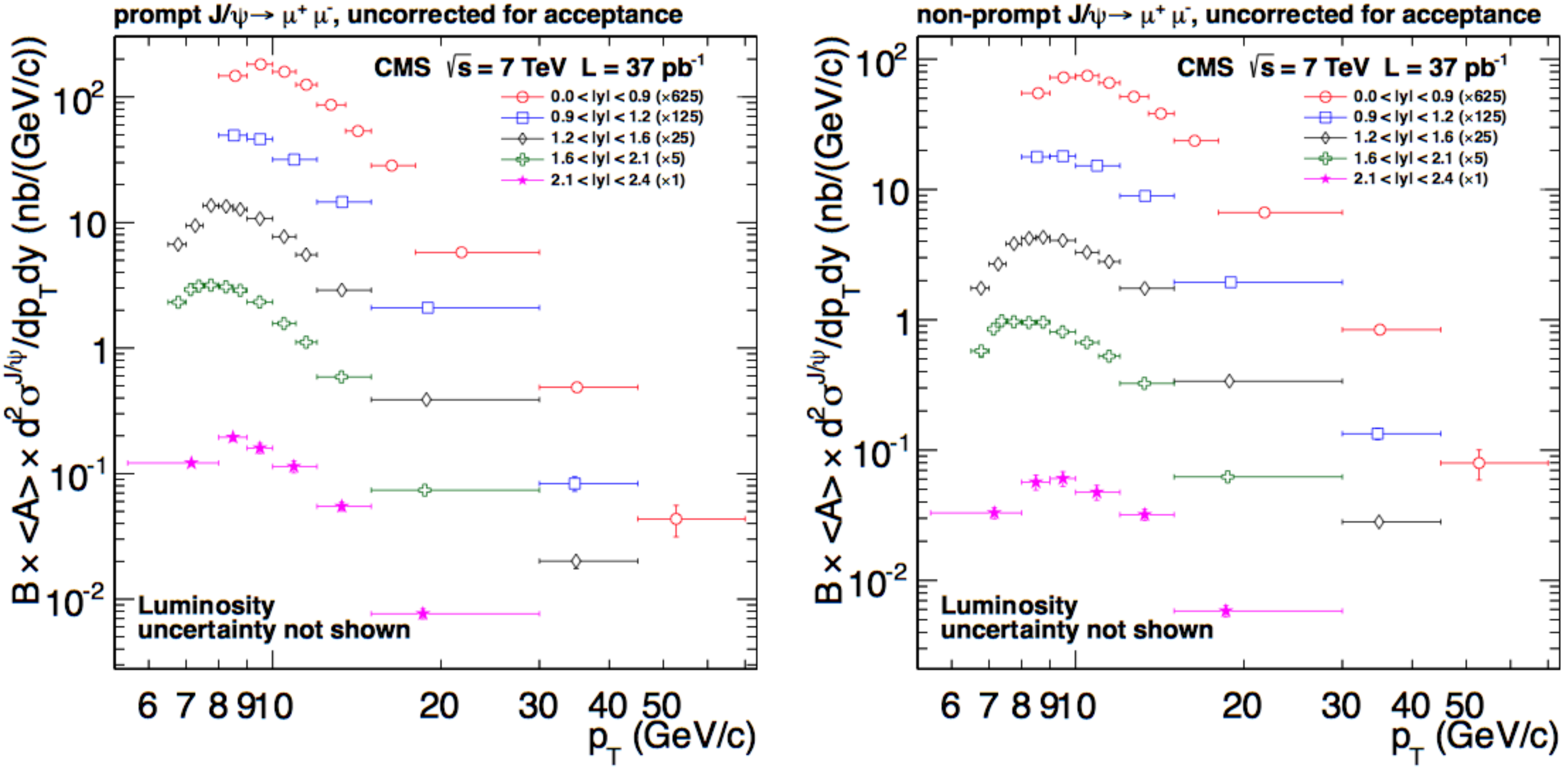
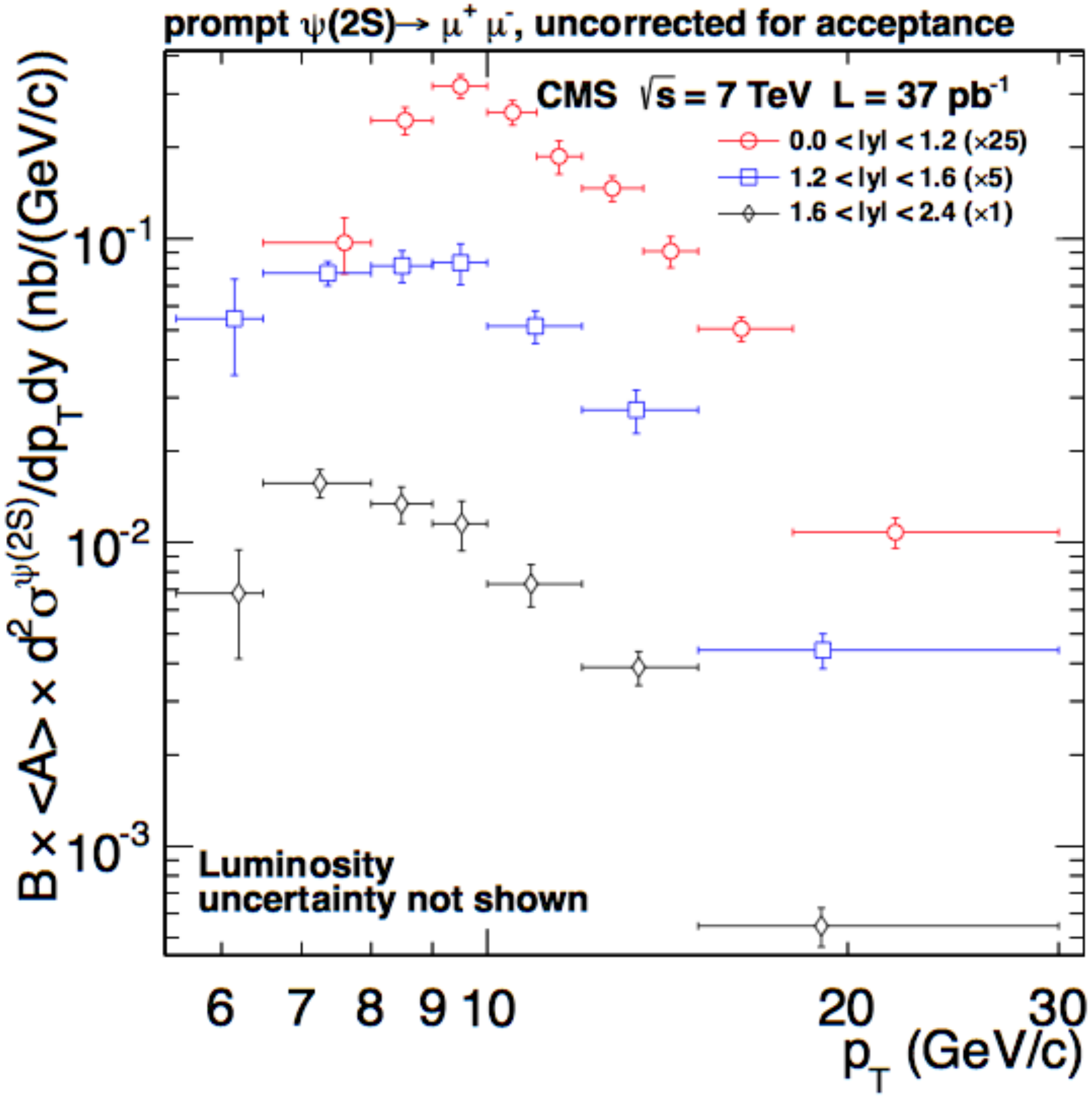


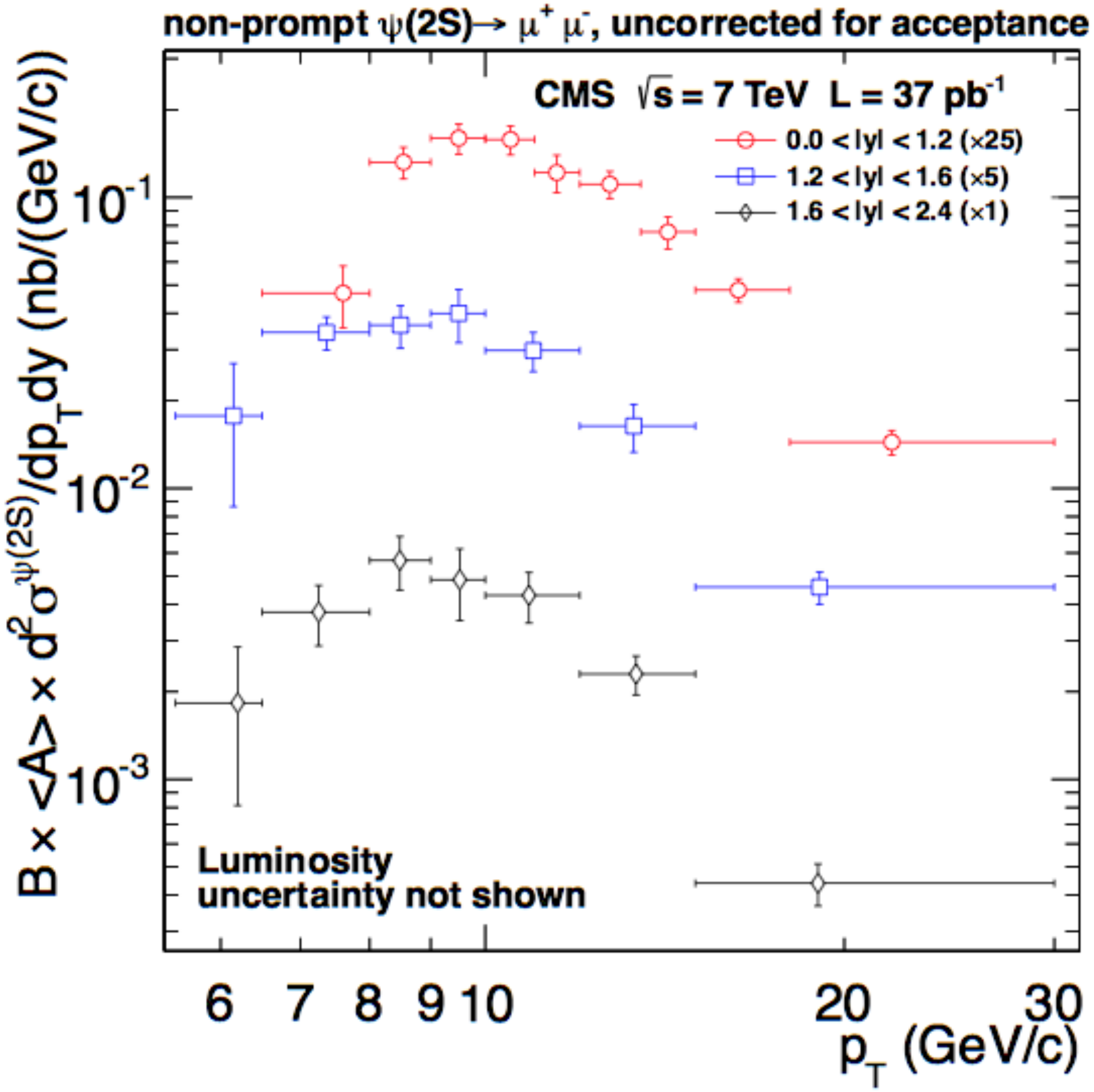
- Uncorrected for acceptance

CMS-BPH-10-014
arXiv:1111.1557
(accepted by JHEP)

ψ(2S) in pp at $\sqrt{s}$ = 7 TeV

CMS-BPH-10-014





- Uncorrected for acceptance

CMS-BPH-10-014
arXiv:1111.1557
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Υ(2S+3S) Suppression

- Systematic uncertainty: 9.1%
- Statistical uncertainty: 55%
- Null-hypothesis testing:
  - p-value = 1%
  - Significance of suppression is 2.4 σ
- Relative suppression of Υ(2S+3S) vs. Υ(1S)
  - Observation consistent with melting of the excited states only?
- What about cold nuclear matter effects?
  - Shadowing cancelling in the Υ(2S+3S)/Υ(1S) ratio
  - pA run?

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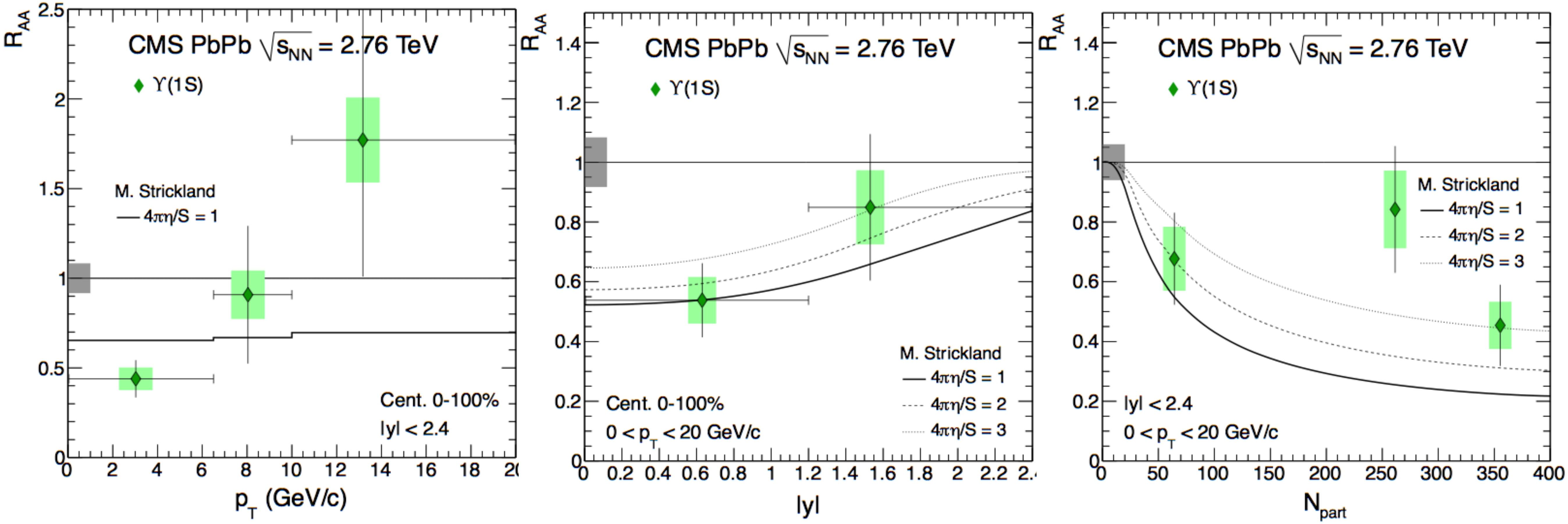
ϒ(1S) R_{AA}

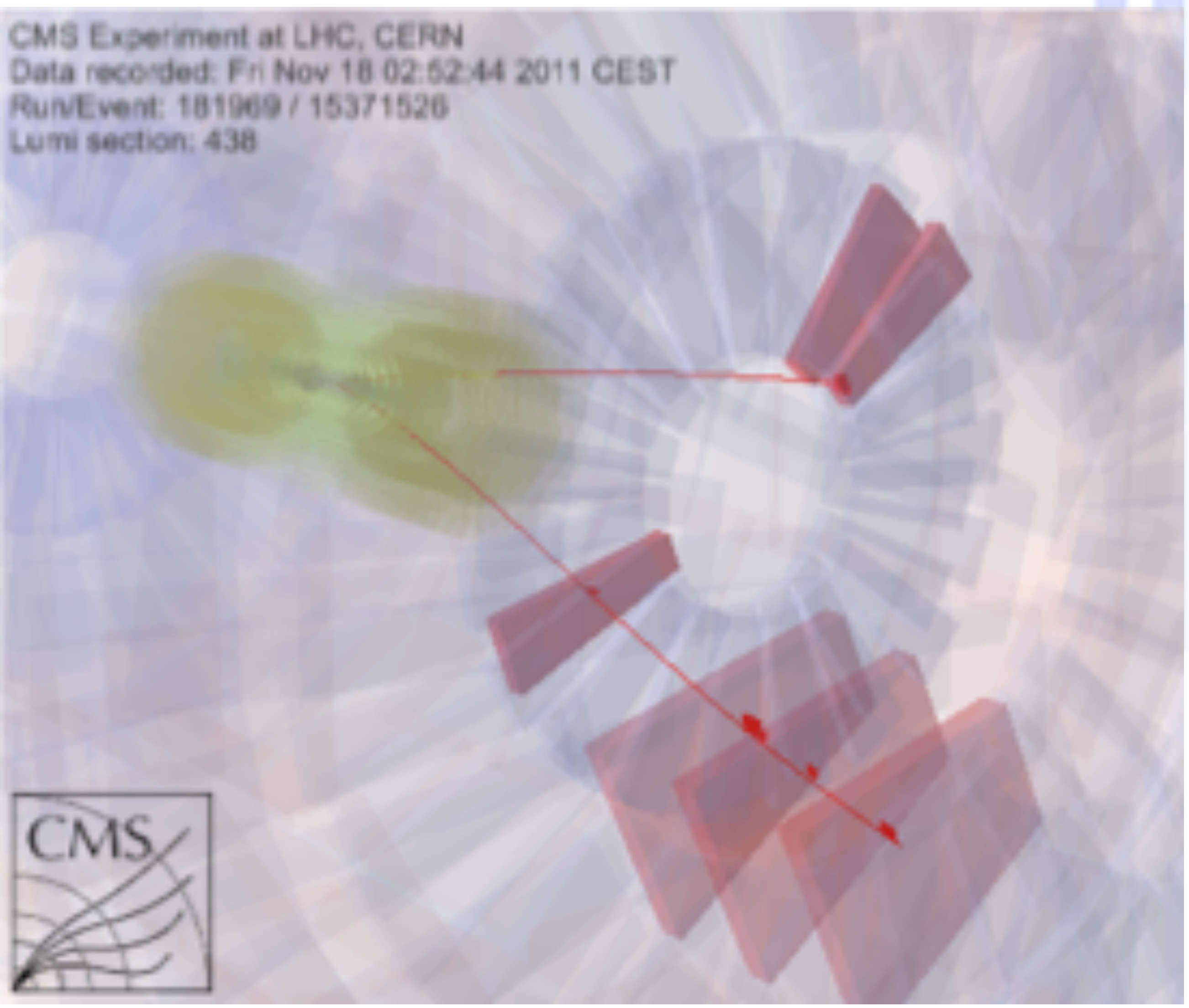


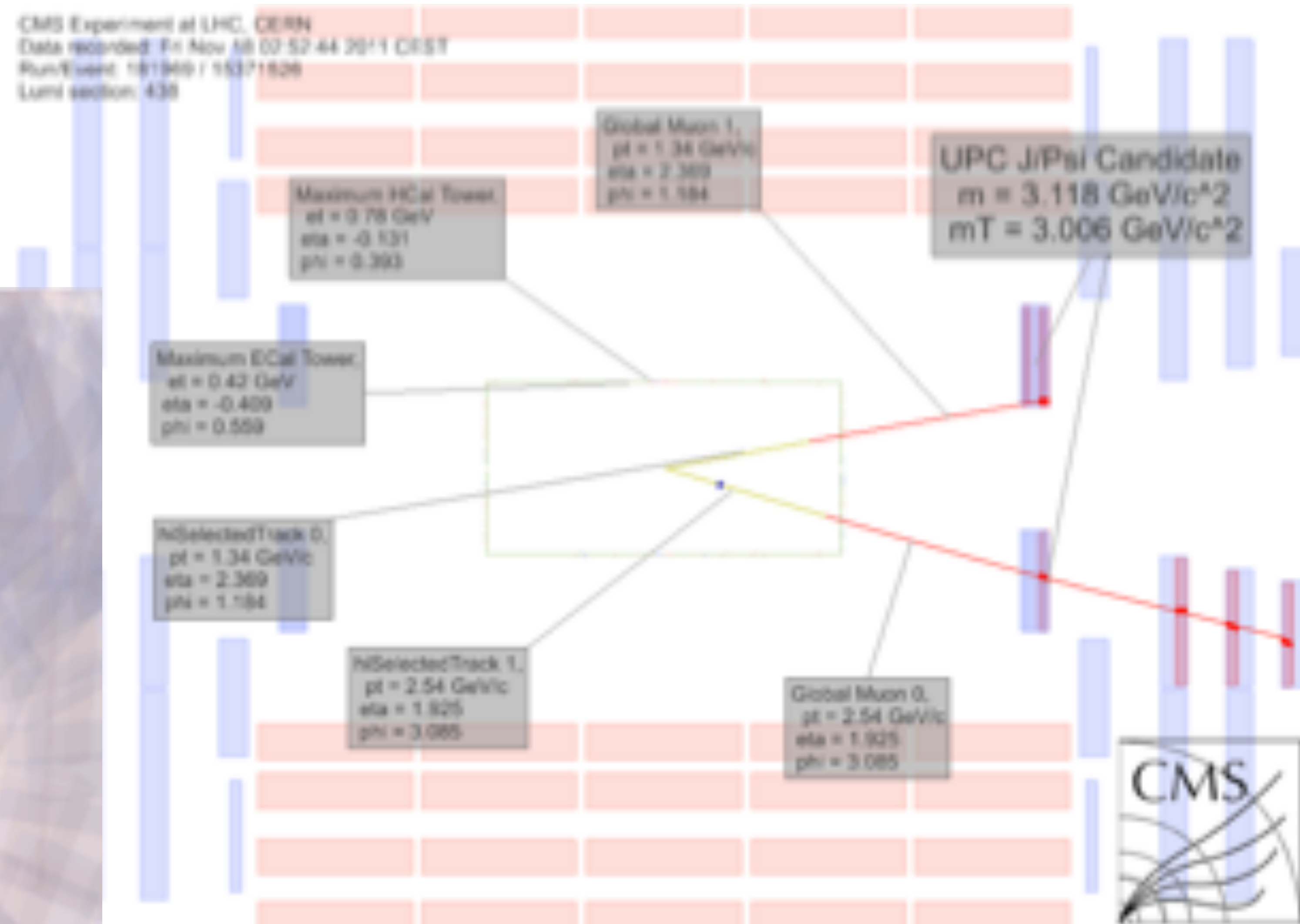
- ϒ(1S) suppressed at low p_T
- No obvious rapidity dependence
- CMS: ϒ(1S)
  - suppressed by factor ~2.2 in 0–10%
- M. Strickland calculates ϒ(1S) and χ_b R_{AA} (arXiv:1106.2571)
  - For feed down: no explicit calculation of ϒ(nS) R_{AA}: assume all states as suppressed as the χ_b
  - Rapidity and centrality dependence in good agreement, but misses suppression at low p_T

CMS-HIN-10-006
arXiv:1201.5069
(accepted to JHEP)

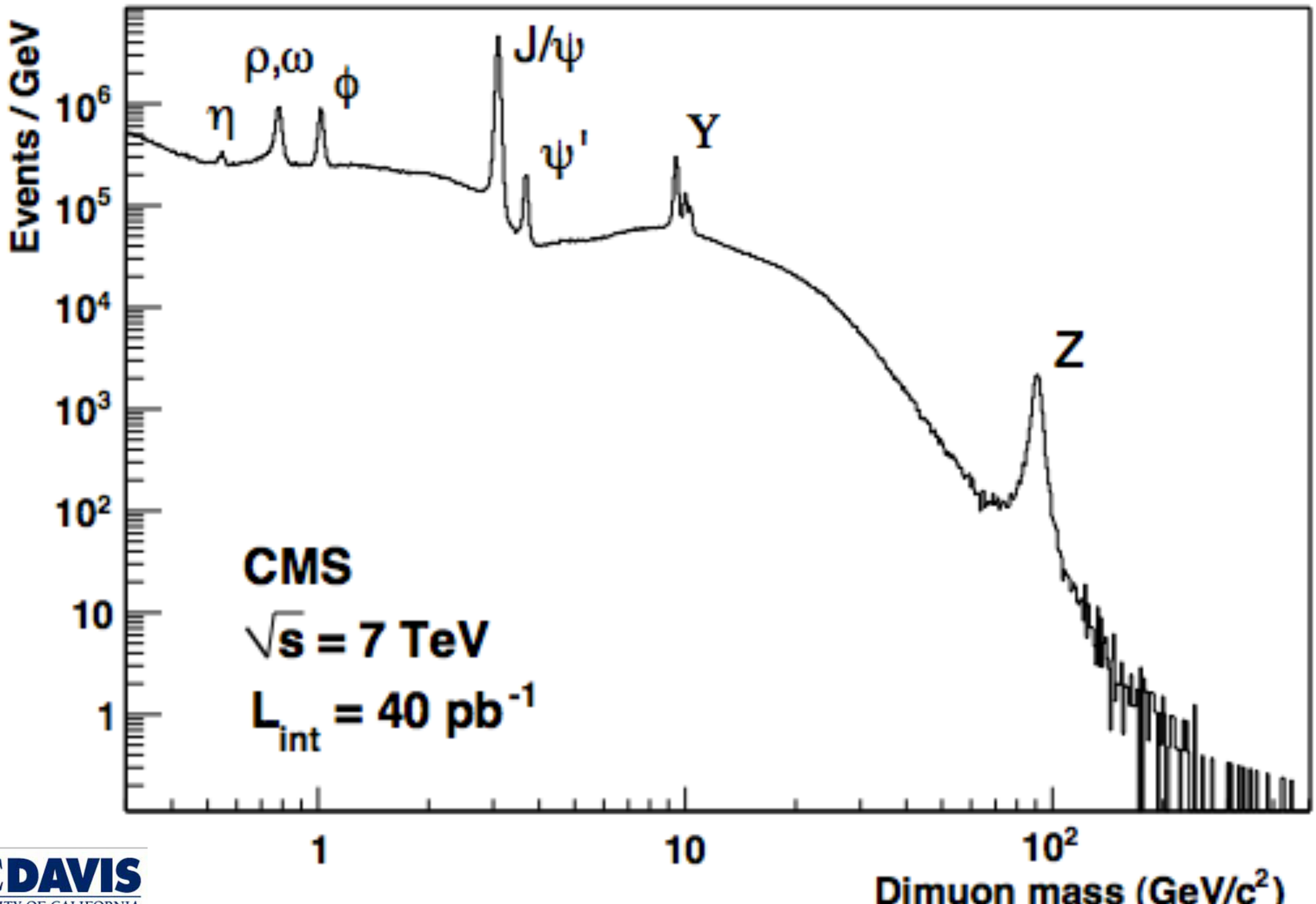
J/ψ in ultra-peripheral PbPb collisions

- Only two tracks in the event (the two muons), barely any energy in the calorimeters, and classified in the 2.5% most peripheral collision bin for heavy ions

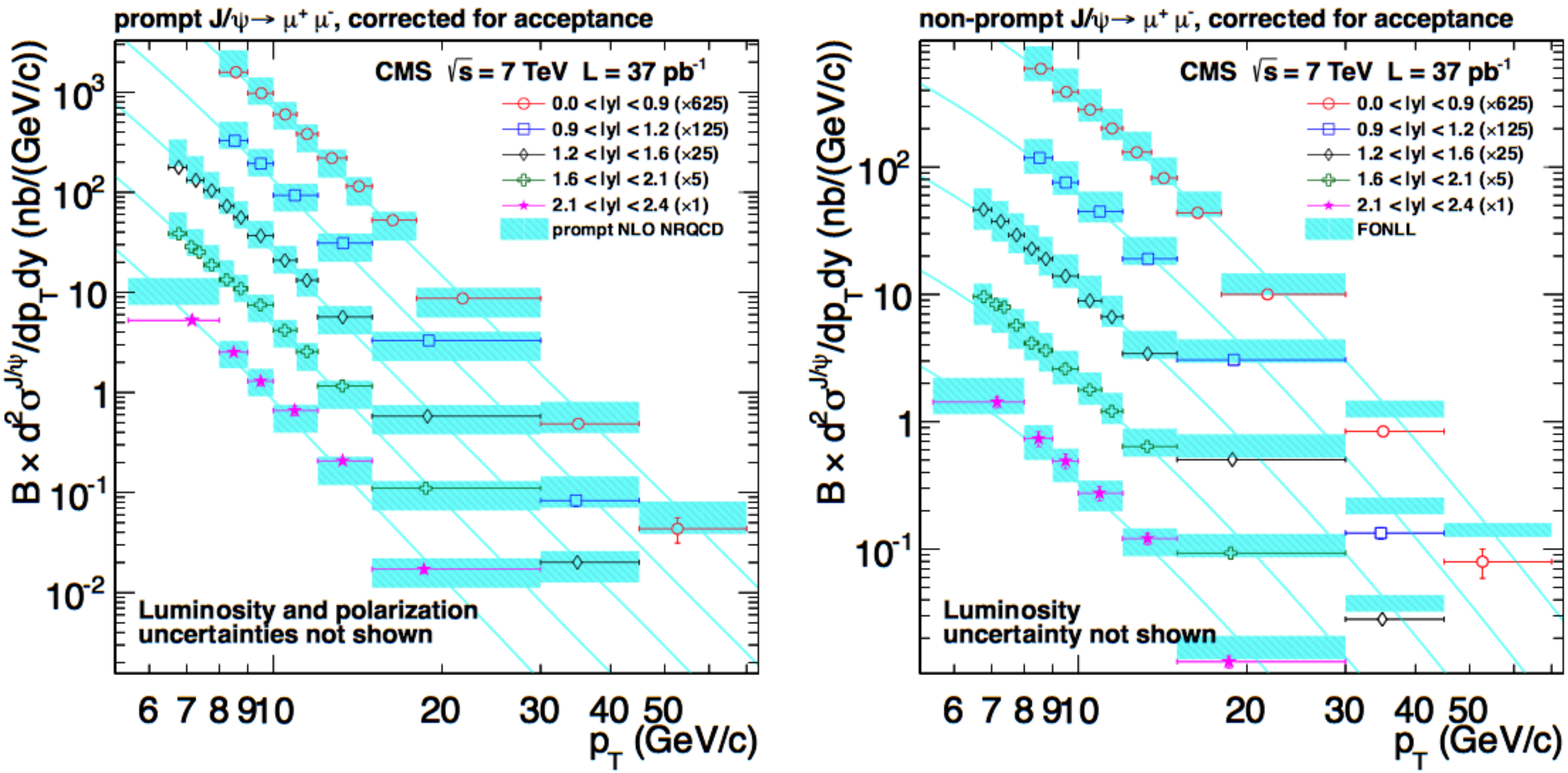




Muon pairs in pp at $\sqrt{s}$ = 7 TeV



J/ψ in pp at $\sqrt{s}$ = 7 TeV



- Prompt J/ψ well described by NRQCD
- Open heavy-flavour:
  - Non-prompt J/ψ fall faster at high p_T than expected from FONLL

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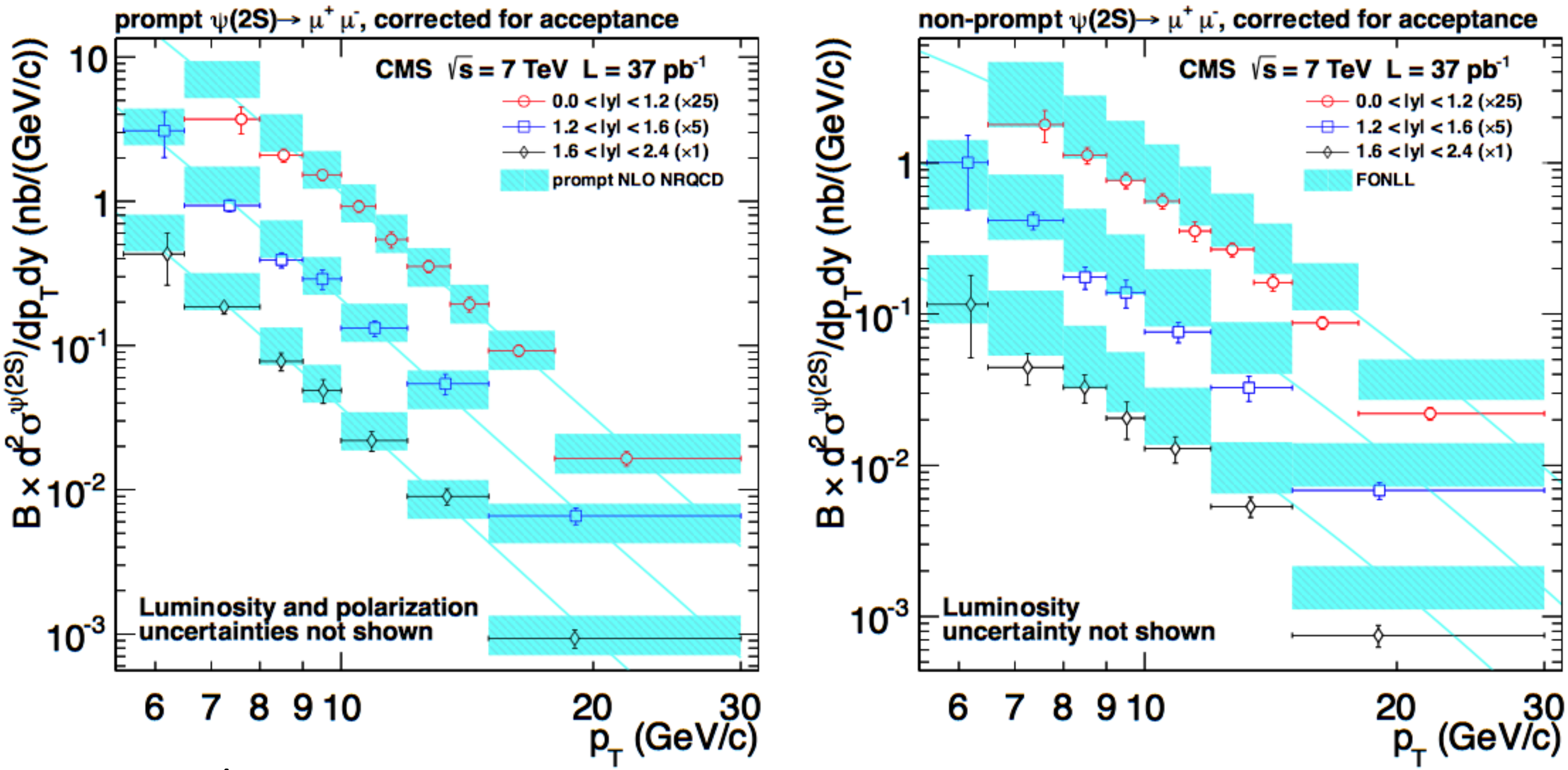
ψ(2S) in pp at $\sqrt{s}$ = 7 TeV



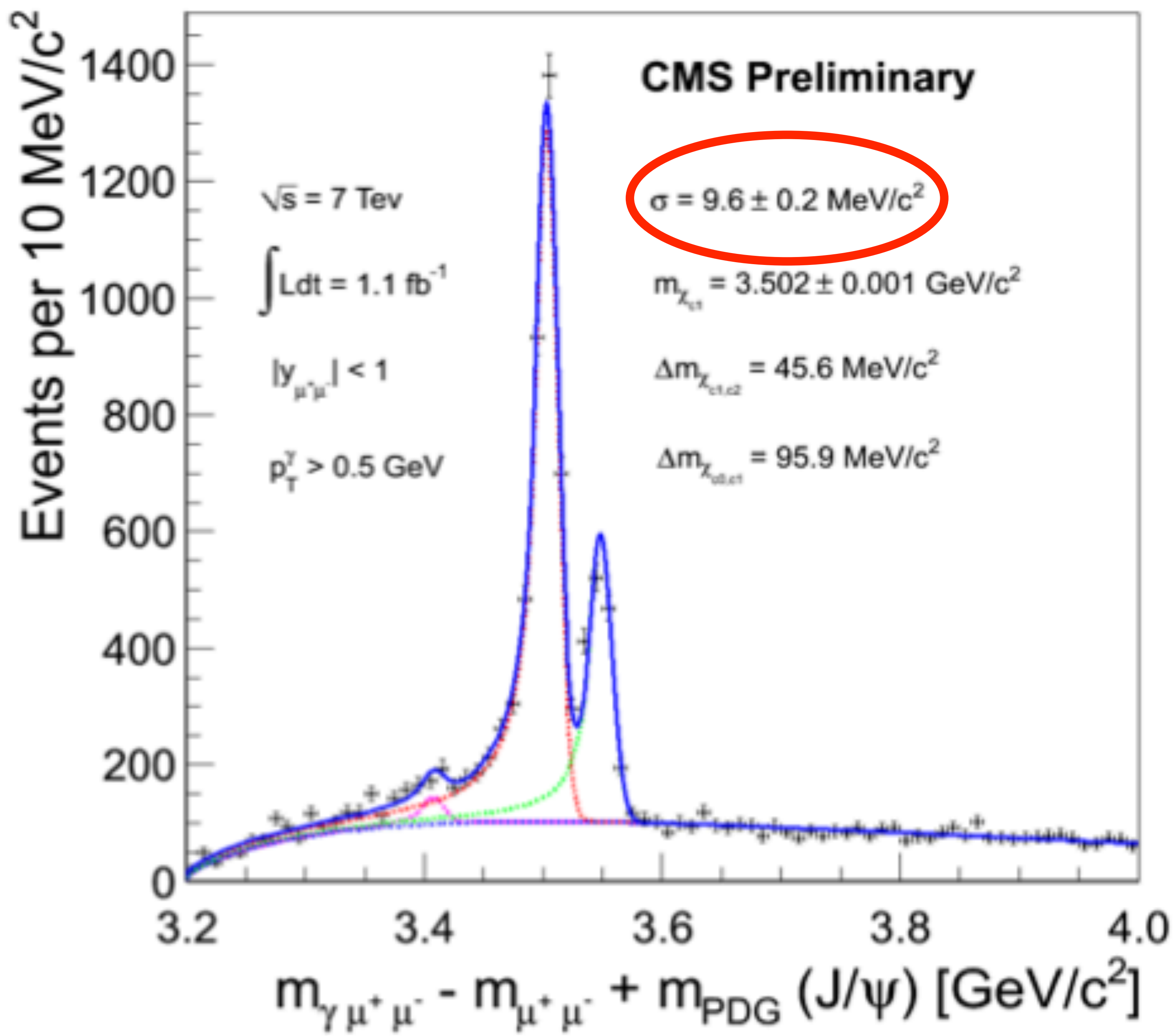
- Prompt ψ (2S) well described by NRQCD
- Open heavy-flavour:
  - Non-prompt ψ (2S) overestimated by FONLL (however, large uncertainty on BR(B→ψ (2S)X))
    - falls faster with p_T than expected from FONLL

CMS-BPH-10-014
arXiv:1111.1557
(accepted by JHEP)

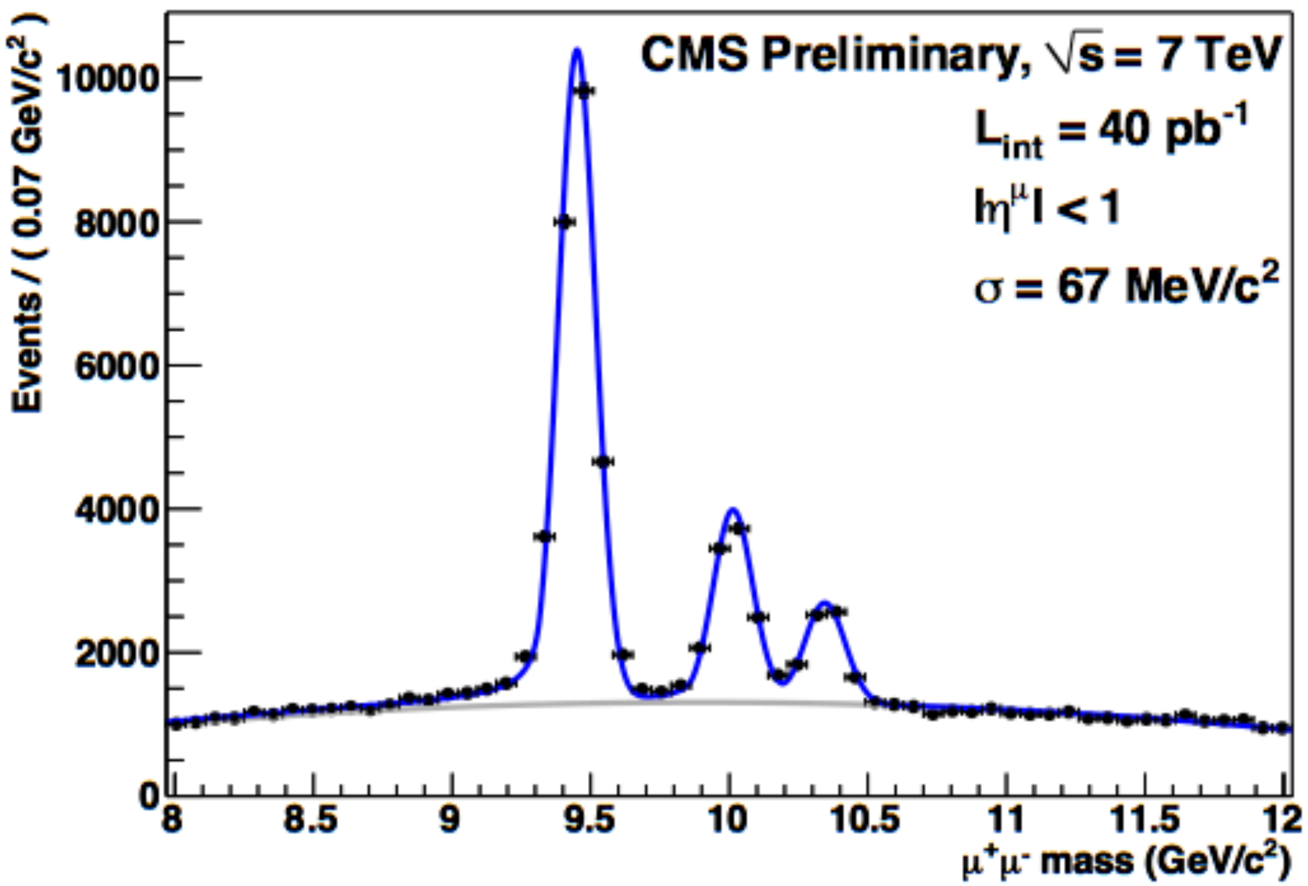
χ_c in pp at $\sqrt{s}$ = 7 TeV

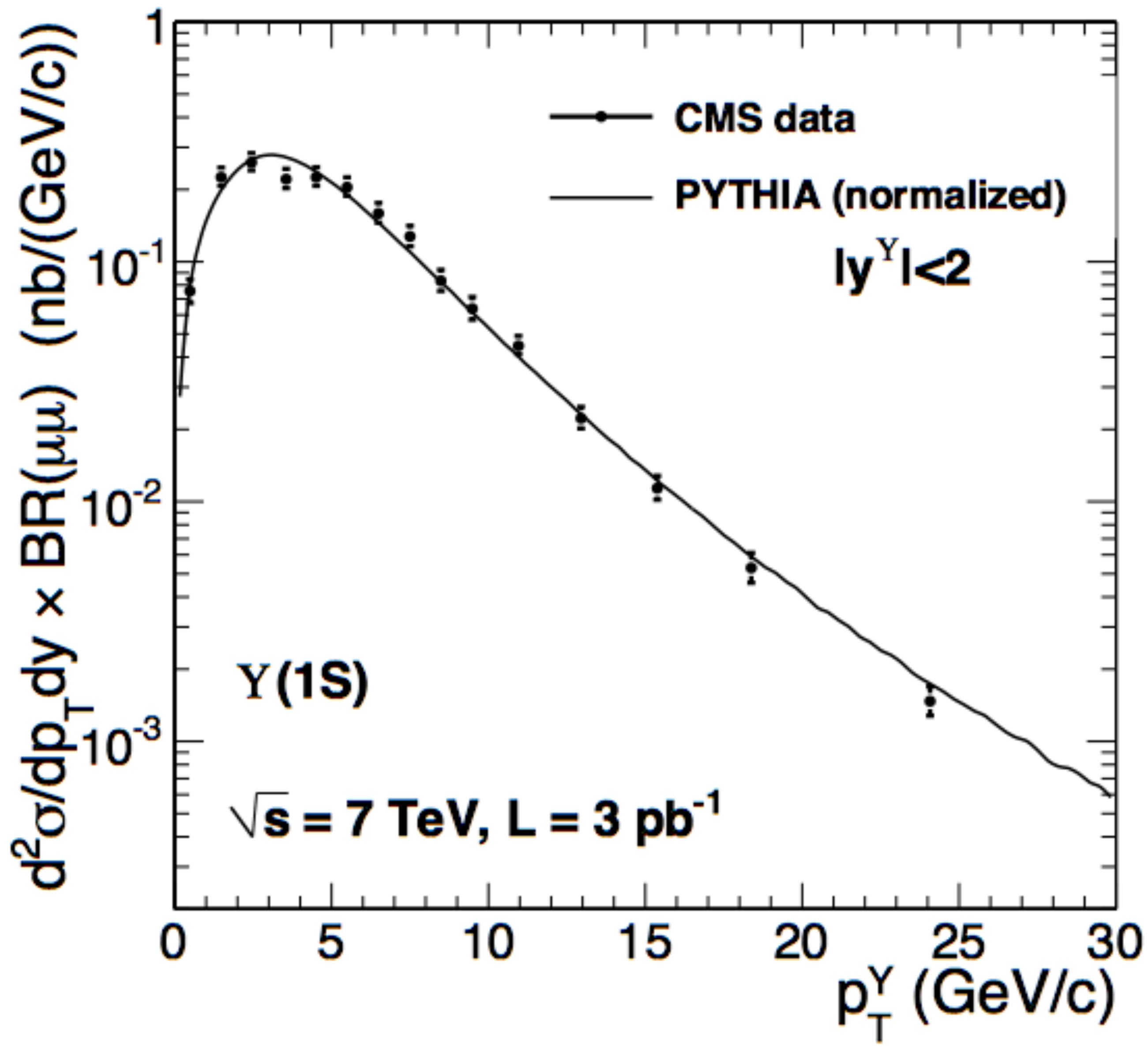
- Measured radiative decay: $\chi_c \rightarrow J/\psi\ \gamma$
- Photon measured by reconstructing e^+e^- conversion pairs
  - Excellent mass resolution $\rightarrow$ separating χ_{c1} and χ_{c2}
  - Hint of χ_{c0}

CMS DPS 2011-011



Υ(nS) in pp at √s = 7 TeV





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- Separation of the 3 Υ states with good mass resolution
- PYTHIA agrees in shape, but not in normalisation
  - Total cross section overestimated by about a factor 2